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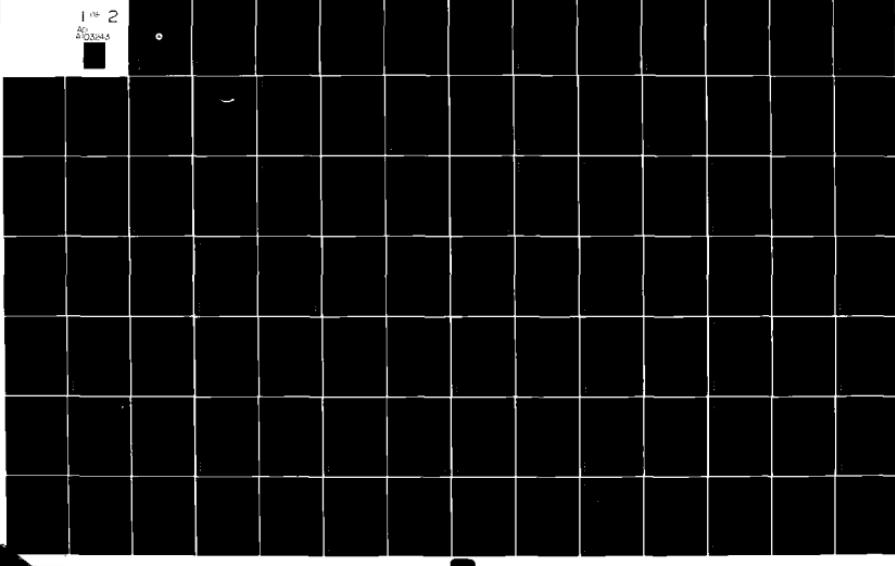
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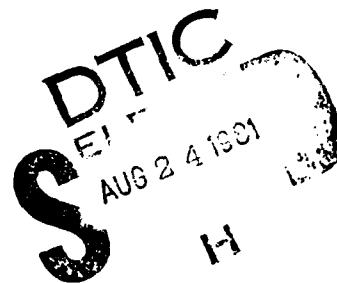
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EVALUATION OF VARIOUS NAVIGATION SYSTEM CONCEPTS

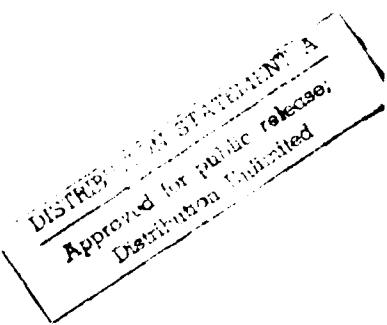
INTERIM REPORT

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July 1981

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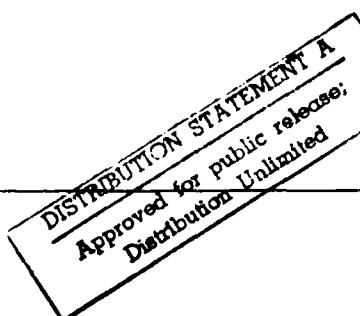


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15. Abstract The purpose of this study is to identify the capabilities and limitations of a particular set of navigation systems and evaluate their performance in the current airspace environment. The navigation systems evaluated are Loran-C, Omega, VHF Omnidirectional Range/Distance Measuring Equipment (VOR/DME), and Global Positioning System (GPS). In addition to detailed technical and operational analyses of each navigation system, consideration is also given to the constraints imposed by and the deficiencies existing in the standards by which accuracy and effectiveness of navigation systems are measured.	16. Key Words Navigation VOR/DME Omega/VLF Loran-C GPS	17. Distribution Statement Unlimited	
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<u>LENGTH</u>				
inches feet yards miles		2.5 30 0.9 1.6	centimeters centimeters meters kilometers	mm cm m km
inches feet yards miles		0.39 0.09 0.8 2.4	square centimeters square meters square kilometers hectares	cm ² m ² km ²
inches feet yards miles		0.4 1.2 0.4 0.4	square centimeters square meters square kilometers hectares (10,000 m ²)	mm ² cm ² m ² ha
<u>AREA</u>				
square inches square feet square yards square miles acres		6.5 0.09 0.8 2.4 0.4	square centimeters square meters square kilometers hectares	cm ² m ² km ² ha
ounces pounds short tons (2000 lb)		28 0.45 0.9	grams kilograms tonnes	g kg t
ounces pounds short tons (2000 lb)		0.035 2.1 1.1	grams kilograms tonnes (1000 kg)	g kg t
<u>MASS (weight)</u>				
ounces pounds short tons (2000 lb)		28 0.45 0.9	grams kilograms tonnes	g kg t
<u>VOLUME</u>				
tablespoons fluid ounces cups pints quarts gallons cubic feet cubic yards		5 15 30 0.24 0.47 0.95 3.8 0.03 0.76	milliliters milliliters liters liters liters cubic meters cubic meters	ml ml l l l m ³ m ³
tablespoons fluid ounces cups pints quarts gallons cubic feet cubic yards		0.03 2.1 1.06 0.26 35 1.3	milliliters liters liters cubic meters cubic meters	ml l l m ³ m ³
<u>TEMPERATURE (exact)</u>				
Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C	°F °C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<u>LENGTH</u>				
mm cm m km		0.04 0.4 3.3 1.1	inches inches feet feet yards yards miles miles	in in ft ft yd yd mi mi
mm cm m km		0.5	kilometers	km
mm cm m km		0.16 1.2 0.4 2.5	square centimeters square meters square kilometers hectares (10,000 m ²)	m ² m ² m ² ha
<u>AREA</u>				
mm cm m km		0.035 2.2 1.1	grams kilograms tonnes (1000 kg)	g kg t
mm cm m km		0.03 2.1 1.06 0.26 35 1.3	milliliters liters liters cubic meters cubic meters	ml l l m ³ m ³
<u>VOLUME</u>				
mm cm m km		32 80 120 160 200	°F °C	°F °C
mm cm m km		37 40 50 60 70 80 90 100	°F °C	°F °C
<u>TEMPERATURE (exact)</u>				
°F °C	5/9 (after subtracting 32)	Celsius temperature	°C	°F °C

¹ Note: 2 3/4 inches = 7 cm. Other such conversions and more tables see NBS Special Publication No. C13-15, 25, 30, 35.

Units of Weights and Measures

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pp 25-30

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SUMMARY

This interim report documents the current status of work performed by ARINC Research under contract to the Federal Aviation Administration (FAA) to evaluate various navigation concepts. The purpose of this study is to compile and illuminate those technical and operational parameters which have the greatest impact on the compatibility of navigation systems operating in common airspace. Assessments were made concerning the validity of analyses previously performed by recognized authorities in the field of navigation, and no need was found to conduct new analyses or to duplicate past analyses. The conclusions generated in this study are therefore based on existing reference material.

The navigation systems evaluated in this interim report, both independently and in various combinations, are Loran-C, Omega, VHF Omnidirectional Range/Distance Measuring Equipment (VOR/DME), and Global Positioning System (GPS). The final report will include evaluations of Doppler and inertial navigation systems in addition to the material contained in this interim report.

Although the primary focus of this study is on the technical and operational characteristics of navigation systems, economic and institutional issues are also discussed briefly. The technical performance capability of each navigation system is compared with existing accuracy requirements. Systems that are capable of satisfying the accuracy requirements are then evaluated to determine what limitations are imposed by signal coverage considerations. This analysis shows that, in terms of the currently used systems evaluated in this study -- Loran-C, Omega, and VOR/DME -- there is no unnecessary proliferation of navigation systems. This particular combination of navigation systems appears to satisfy current domestic, oceanic, and offshore navigation user requirements. No single system existing today as a fully operational navigation system can meet all of these requirements.

Each system is also evaluated, independently and in various combinations, in an operational sense through the application of realistic flight procedure scenarios. These case studies identify a number of sources of conflict that could affect the integrity of position determination, pilot workload, Air Traffic Control (ATC) controller workload, and air safety. Although Loran-C, Omega, VOR/DME, and GPS navigation systems independently

meet existing performance requirements as they apply to established VORTAC-referenced airways,* the errors associated with their use in an area navigation application can combine in a way that causes lateral deviations about a geographic centerline exceeding current specifications for route width. The results of this study indicate that unrestricted use of area navigation systems in the current structure of the airspace is not advisable until some form of standardization is established in a number of areas, including the following:

- Path definition (e.g., great circle or rhumb line)
- Earth model (e.g., spherical, Clarke 1866, or WGS-72)
- Propagation models (i.e., sky waves and grounds waves)

*VOR facilities collocated with Tactical Air Navigation (TACAN) facilities are classified as VORTACs.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The continuing growth of aviation traffic, in both general aviation and commercial airlines, places increasing demands on the national navigation system. Higher densities of commercial and general aviation aircraft will demand more accurate positioning en route than is now required. To ensure a satisfactory integrated national navigation system capable of meeting anticipated requirements, the Federal Aviation Administration (FAA) is conducting strategic studies and planning with regard to possible navigation concept scenarios to be adopted between now and 1995. The strategic studies of the FAA require an accurate, detailed assessment of these concepts and of the capabilities, costs, and interdependencies of the possible navigation systems that may be applied to meet anticipated navigation requirements.

Consequently, the FAA contracted ARINC Research to study critical aspects of current and future navigation systems and practices. This interim report presents the current status of work involving the evaluation of various navigation system concepts in the context of the existing airspace environment.

1.2 PURPOSE

The *Federal Radionavigation Plan* (FRP) directs responsibility to the Departments of Transportation and Defense to select a suitable mix of radio-navigational systems that can meet the diverse technical, operational, and economic requirements imposed by users, manufacturers, and the Air Traffic Control system. The purpose of this study is to compile and illuminate those technical and operational parameters which have the greatest impact on the compatibility of navigation systems operating in common airspace. Assessments were made concerning the validity of analyses previously performed by recognized authorities in the field of navigation, and no need was found to conduct new analyses or to duplicate past analyses. The conclusions generated in this study are therefore based on existing reference material.

1.3 SCOPE

This study reviews the technical and operational characteristics of Loran-C, Omega, VHF Omnidirectional Range/Distance Measuring Equipment (VOR/DME), and Global Positioning System (GPS) navigation systems. The systems are evaluated both independently and in various combinations. The evaluations are in the form of comparative analyses -- the systems are compared with each other as well as with existing FAA technical and operational requirements. Conclusions concerning the effectiveness of particular navigation systems in satisfying the stated requirements are presented, along with recommendations for improving operational performance. Commentary is also included concerning inadequacies in formulating accuracy requirements. Finally, the study recommends a combination of navigation systems that will provide the greatest potential for acceptance as the primary means for navigation in the context of the current airspace environment.

1.4 TECHNICAL APPROACH

Technical and operational capabilities of each navigation system under consideration were identified through literature searches and discussions with manufacturers and users. Performance requirements as specified by the FAA were obtained from the recently published FRP and from previously issued FAA Advisory Circulars. Technical capabilities of each system were then compared with the requirements. The results of these comparisons were used to categorize each system with respect to which flight phases could be accommodated in a purely technical sense, using both statistical and measured navigation system capabilities. The systems were then evaluated to determine their operational capability in specific case studies. The scenarios selected for the case studies were representative of typical situations that are encountered frequently. The operational capability of each navigation system in each scenario was defined on the basis of selected measures of performance. The degree of system interoperability was determined and discussed in terms of potential conflict in each scenario as a function of the relative differences in operational capability between system types. It was possible to interpret the capabilities and limitations of various system combinations by integrating the results of each case study with the results of the technical evaluation. This assessment led to recommendations of which system mixes should be supported by the FAA and also provided insight into the factors that tend to limit full exploitation of currently available navigation system capability. This report suggests steps that can be taken to overcome these limitations.

1.5 REPORT ORGANIZATION

Chapter Two defines terms used throughout the report and presents summary descriptions of the navigation systems discussed, along with a summary of the operational features of the airborne equipment associated with each of those systems.

Chapter Three details the performance requirements as specified by the FAA that any navigation system must satisfy to be acceptable for use.

Chapter Four contains detailed analyses of the technical capabilities of each navigation system and compares these capabilities with the requirements.

Chapter Five provides insight into the operational capabilities of each navigation system, both independently and in combination with other systems, through specific case studies.

Chapter Six presents conclusions and recommendations.

Appendix A provides detailed descriptions of each navigation system, and Appendix B contains the equations used in computing some of the navigational errors specified in the report.

Appendix C lists the references cited in this report, along with other source material.

CHAPTER TWO

NAVIGATION SYSTEMS OF INTEREST

2.1 DEFINITIONS

The following sections define navigation concepts that are extensively referred to throughout this report.

2.1.1 Radionavigation

Navigation is the process by which a vehicle is directed from one known position to another known position. Navigation systems characterized by their use of radio waves for determining position are known as radionavigation systems. Included in the category of radionavigation systems are Loran-C, Omega, VOR/DME, Tactical Air Navigation (TACAN), and GPS navigation systems; these will be discussed in detail in this report. Other navigation systems that utilize the radio wave spectrum but are not included in this report are Loran-A, instrument landing system (ILS), microwave landing system (MLS), the Navy Navigation Satellite System (TRANSIT), radio beacons, Decca, and radar.

The Loran-A navigation system has been replaced by Loran-C, ILS and MLS are landing systems, and TRANSIT navigation does not provide continuous coverage and is therefore not suitable as a primary means of navigation. Although radio beacons may be an element of a navigation system mix, their lack of sufficient navigational accuracy precludes their use as a primary system. The Decca navigation system has coverage limitations that make it less suitable than Loran-C, and radar is primarily used for ground surveillance, not navigation. Radar vectors are issued by air traffic controllers and accepted by pilots as a means of navigation. However, because they do not constitute a primary form of navigation, they are not discussed as such in this report.

A number of navigation systems are derivatives of a primary system. For example, basic VOR has led to the development of wide aperture (digital) VOR, Doppler VOR, and precision VOR. The study of system derivatives is outside the scope of this report.

2.1.2 Area Navigation

Area navigation is an application of the navigation process, providing the capability to establish and maintain a flight path on any desired

course that remains within the coverage area of the type of navigation signals being used. This random navigation capability is generally referred to as RNAV. Loran-C, Omega, and GPS are inherently RNAV navigation systems. VOR/DME in its basic form is station-referenced and therefore is not an RNAV system. However, more sophisticated airborne VOR/DME processors provide RNAV capability.

2.1.3 Hyperbolic Navigation

Hyperbolic radionavigation systems determine position through difference measurements of signals from three transmitting stations. These measurements can either be time differences (the elapsed time between the arrival of signals from two stations) or phase differences measured between two signals.

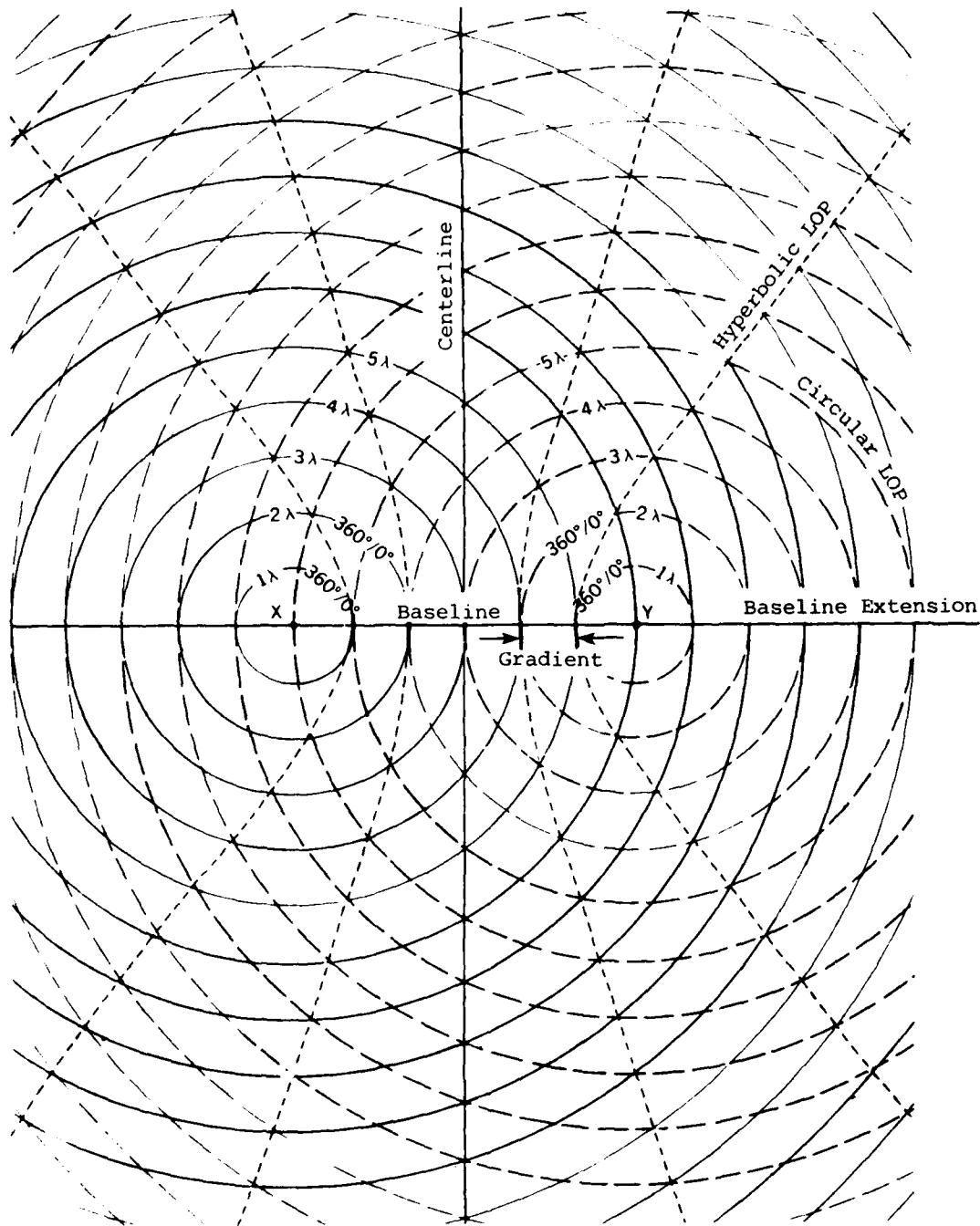
A transmitter that emanates signals in all directions creates a circular waveform, with the transmitter at the center of the circle and all points on the circle equidistant from the transmitter. A series of circles can be defined as being successively larger units of distance (wavelengths) from the transmitter. If signals are transmitted from two stations at the same time, they will meet along a line equidistant from the two stations. This line, referred to as the centerline, is the perpendicular bisector of a line drawn between the two stations, called the baseline. Figure 2-1 illustrates this.

Reception of the two signals from a point not on the centerline will result in a measured difference in time or phase. The locus of points at which the same difference can be measured defines a hyperbola. The time or phase difference measured corresponds to a distance difference. Each hyperbola in Figure 2-1 is a line of position (LOP), representing a constant range difference from the two transmitters. When a user is along the line connecting the two stations but is not between those two stations, the user is on a baseline extension. The farther a user is from the baseline along a given LOP, the larger the spacing, or gradient, between consecutive LOPs per unit measurement difference. The width of this spacing is referred to as a lane. In regions of a high gradient, a relatively low time- or phase-difference error will cause a relatively high position error. The gradient is so high along the baseline extensions that navigation is avoided in those areas.

Although a user can determine which LOP corresponds to his difference measurement, he is unable to locate his point of position along the LOP. A second LOP can be defined through the use of a third station, with a second baseline being drawn between the third station and either of the first two stations. The intersection of the two LOPs defines a position fix, illustrated in Figure 2-2.

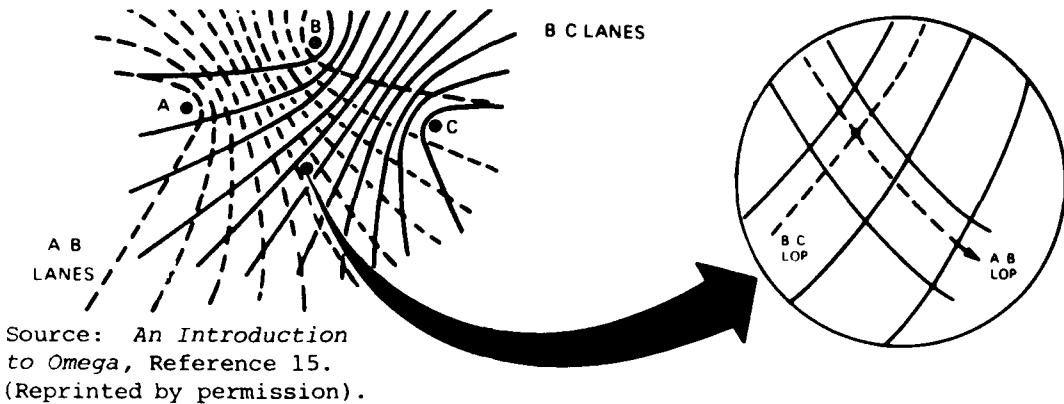
2.1.4 Rho-Rho Navigation

In hyperbolic navigation, time or phase differences are measured to provide knowledge of aircraft position in relation to the distance between stations. The distance between the aircraft and a ground station is commonly referred to as range, or rho. Rho-rho navigation involves directly measuring the total time it takes for each of two signals to travel from



Source: American Practical Navigator, Reference 1.

Figure 2-1. HYPERBOLIC NAVIGATION GEOMETRY



Source: *An Introduction to Omega*, Reference 15.
(Reprinted by permission).

Figure 2-2. HYPERBOLIC POSITION FIX

separate transmitters to the airborne receiver. Each time measurement corresponds directly to a range measurement and defines a circular LOP. This form of operation is referred to as the ranging mode. The intersection of two circular LOPs provides two possible position fixes; the ambiguity is easily resolved by knowledge of approximate position.

The gradient between LOPs in the hyperbolic mode increases in accordance with the divergence of the hyperbolas. In the ranging mode, however, the gradient between the circular LOPs is constant, as shown in Figure 2-1. Therefore, navigation at extended ranges from the baseline is possible with use of the ranging mode, thereby effectively increasing the coverage area of the stations. In addition, whereas hyperbolic navigation requires three stations, rho-rho navigation requires only two stations. Greater freedom in selecting stations allows for consideration of station-to-user geometry to improve accuracy. The area covered by the system is also extended beyond that possible for hyperbolic navigation by the requirement that the user be within range of only two stations rather than three.

A disadvantage of rho-rho navigation is the user requirement for a highly stable, and therefore costly, time source (local oscillator or clock) against which the time measurements are made. Any clock drift will directly affect the range measurement. Clock bias is not a factor in the hyperbolic mode, since time differences between signals are measured.

2.1.5 Rho-Rho-Rho Navigation

When a third station is used to complement the two range measurements of the rho-rho mode, three circular LOPs are generated. The three LOPs will intersect at a common point only if there are no clock errors. By adjusting the range measurements until common intersection is achieved, clock drift can be estimated and applied to subsequent range measurements. This technique allows the use of a less expensive clock, but necessitates the use of three stations.

2.1.6 GDOP

The effect that geometry between the user and the signal transmitters has on accuracy is expressed in terms of geometric dilution of precision (GDOP). A GDOP of 1 corresponds to the best geometry configuration, while progressively larger values of GDOP indicate worsening geometry.

For hyperbolic navigation, geometrical considerations include the crossing angle of intersecting LOPs and the spacing between consecutive LOPs. The most favorable geometry occurs along baselines with the two intersecting LOPs being nearly orthogonal. As the crossing angle becomes more shallow, the ability to resolve the point of intersection becomes less distinct. Uncertainty in time or phase measurement translates into a position error, the magnitude of which is a function of the distance between LOPs (the lane width). A certain percentage of uncertainty in determining position within a lane will result in larger errors for wider lanes. The lane width widens between hyperbolic LOPs with increasing distance from the baseline, resulting in degradation of accuracy corresponding to typical GDOPs of 2 to 3.

2.2 SYSTEM SUMMARIES

The following sections briefly summarize the systems evaluated in this report. Detailed descriptions are provided in Appendix A.

2.2.1 Loran-C

Loran-C is a hyperbolic radionavigation system that uses ground waves at low frequencies to obtain an operating range of approximately 1,000 miles independent of line-of-sight. It also uses pulse techniques to avoid sky-wave contamination. Accuracy of Loran-C is highly dependent upon GDOP factors at the user's location within the coverage area. Loran-C is capable of achieving absolute 2 drms* accuracies of 463 meters (0.25 nautical miles [nm]) or better. The repeatable and relative accuracies of Loran-C are usually between 18 and 90 meters (0.01 and 0.05 nm). The Loran-C system currently consists of 16 chains operating throughout the world, comprising a total of 51 transmitting stations. Two-thirds of the continental United States and Alaska is currently within the Loran-C coverage area; there is no Loran-C coverage in the Southern Hemisphere. Loran-C coverage is concentrated in the coastal areas of the Atlantic and Pacific oceans and the Norwegian and Mediterranean seas.

2.2.2 Omega

Omega is another hyperbolic navigation system, but one that utilizes sky waves rather than ground waves to give each transmitter an operating range of about 5,000 miles. The accuracy of the Omega system is limited by the accuracy of the propagation corrections that are applied to the received signal; a predictable accuracy of two to four nm is the design

*The concept of drms is defined in Section 3.2.

goal of the system. Statistical studies conducted in the North Atlantic show that rms positional accuracies of one to two nm are possible.

Omega signals transmitted from eight stations provide nearly worldwide coverage. There are also a number of United States Navy very low frequency (VLF) communication transmitters located around the world that can be used as supplementary signal sources for Omega navigation. Use of VLF communication stations improves the dependability and accuracy of continuous coverage during Omega/VLF navigation. A wider choice of candidate stations provides greater probability that GDOP can be minimized by judicious station selection. The extent of infusion into the marketplace of the Omega/VLF concept is making Omega/VLF the dominant form of Omega navigation.

Another recent development in the evaluation of Omega navigation has been the increasing use of ranging techniques rather than the hyperbolic technique in the airborne processor. The ranging mode requires reception from only two stations (rather than the three required in the hyperbolic mode) to obtain a position fix and provides capability for increased coverage and accuracy. However, it is necessary to employ a highly accurate, and therefore expensive, clock for rho-rho measurement. As explained previously, using a third station in a rho-rho-rho mode permits use of a less expensive clock.

2.2.3 VOR/DME

The primary en route navigation system used within the continental United States is VOR/DME. VOR (VHF Omnidirectional Range) provides the azimuth relative to the VOR ground station, while DME (Distance Measuring Equipment) furnishes a measurement of distance from the aircraft to the DME ground station. In most cases, VOR and DME are collocated as a VOR/DME facility. TACAN is a combination of omnibearing and distance-measuring functions. Because TACAN is a military system, the azimuth portion of a TACAN facility is not widely used by nonmilitary users. The distance-measuring function of TACAN, however, is a DME and is therefore accessible to anyone with a DME interrogator. So that both military and civil aircraft can navigate using the same airway network, TACAN facilities are collocated with VOR facilities. A VOR collocated with a TACAN is classified as a VORTAC. Since there is no difference in operation or performance between a VORTAC and a collocated VOR/DME, VORTACs will be included in the VOR/DME system classification in this report.

VOR and DME navaids are most commonly used in one of the following three configurations:

- VOR only
- VOR/DME
- DME/DME

The VOR system forms the basis for defining airways and is therefore an integral part of air traffic control procedures. Use of VOR in the absence of DME results in navigation based solely on directional information. This singular capability is the basis upon which Victor airways were established

-- VOR-to-VOR navigation. By charting the bearing information obtained from two VOR stations, a position fix can be determined. The combination of VOR and DME at a single site provides the capability for position fixing by use of a single facility. This configuration forms the standard International Civil Aviation Organization (ICAO) short-range navigation system. The use of dual DME offers a significant improvement in position-determination accuracy in areas that have suitable dual-DME signal coverage.

The accuracy of VOR is the basis of the design specification for United States air traffic control standards and procedures. The magnitudes of both accuracy and signal coverage of VOR and DME are a function of aircraft altitude and distance from the station. Line-of-sight limitations restrict coverage to 30 nm or less at ground level, progressively increasing with altitude to an upper limit approaching 200 nm.

VOR signal coverage is a function of the class of VOR station: terminal, low altitude, or high altitude. A terminal VOR provides coverage for an altitude range of 1,000 to 12,000 feet at radial distances out to 25 nm; a low-altitude VOR provides coverage from 1,000 to 18,000 feet at radial distances out to 40 nm. The coverage provided by a high-altitude VOR is a function of aircraft altitude, as shown below:

Coverage of radial distances of:	Is provided at altitudes of:
40 nm	1,000 feet to 14,500 feet
100 nm	14,500 feet to 60,000 feet
130 nm	18,000 feet to 45,000 feet

These operational coverage areas can be expanded under special circumstances by extending the coverage radius to no more than 110 nm at altitudes below 18,000 feet, or 185 nm above 18,000 feet.

2.2.4 GPS

The NAVSTAR Global Positioning System (GPS) is a proposed space-based radionavigation system that is intended to provide accurate navigation and position information to all properly equipped users. The fully operational system will enable continuous worldwide navigation regardless of weather conditions. Current plans for GPS call for a constellation of 18 satellites -- a reduction from the 24 in the original specification. Using signals from four satellites, a user can obtain three position dimensions (latitude, longitude, and altitude), determine time, and derive velocity.

Although GPS is a military system, its potential use for civil navigation is a major topic of discussion and study. Current plans call for exclusive military use of the precision code (P-code) which, in the context of an 18-satellite constellation, enables predictable positioning accuracy of 25 meters (0.01 nm) horizontally and 30 meters vertically (95 percent probability), depending on the capability of user equipment and the user-to-satellite geometries. The navigational accuracy to be made available by the

military to civilian users of the coarse acquisition (C/A) code is currently uncertain; speculation ranges from 30 to 500 meters (0.02 to 0.27 nm).

Three-dimensional navigation coverage requires four GPS satellites to be in view of the user. The accuracy obtained depends on the geometry involved. A substantial increase in GDOP is predicted because of the reduction in the number of satellites from 24 to 18. The impact of increased GDOP on civilian use of GPS is somewhat dependent on which areas of the world are most adversely affected.

2.3 SYSTEM FEATURES

Airborne navigation units have evolved and continue to evolve in accordance with the needs of the various user communities. Consequently, the man/machine interfaces of airborne equipment differ from each other as manufacturers provide special features desired by particular users.

2.3.1 Loran-C

Use of Loran-C for airborne navigation evolved as a supplement to conventional VOR/DME in areas of poor VOR/DME coverage. The inability of VOR/DME to provide offshore signal coverage made Loran-C particularly appropriate for offshore helicopter operations. The Coast Guard uses Loran-C for over-water search and rescue missions, and offshore oil well operators use it for navigating between land and offshore drilling platforms. Since these users require the capability of precise position location, manufacturers have emphasized special features such as stored programmable search patterns and highly accurate ground position and track determination. Until Loran-C is more widely accepted for use along conventional domestic airways, there will be little incentive for manufacturers to include a data base of VOR/DME navigation aids (navaids) to enable the construction of navaid-oriented area navigation routes.

2.3.2 Omega

Airborne Omega navigation is used primarily to serve the needs of international air carriers. Neither VOR/DME nor Loran-C can provide coverage over the oceans. Transoceanic navigation is typically performed by either inertial navigation systems (INSs) or Omega. The inertial systems, however, are limited in accuracy by the accumulation of gyro-drift errors. Omega is frequently used, therefore, to provide periodic updates to the INS and to serve as a back-up navigation system. However, Omega is also certified for use as a primary means of oceanic navigation. The ability of Omega to serve as a worldwide navigation system has prompted manufacturers to provide capabilities that make it operationally efficient in almost any environment. Omega navigation systems generally (1) include a data base of all airports and navaids for use in flight planning, (2) provide the capability for an extensive waypoint list that is useful for long transoceanic/transcontinental flights, and (3) allow selection of track-hold autopilot coupling.

2.3.3 VOR/DME

VOR/DME was developed in response to the basic need for an extensive network of omnidirectional navigation aids. As a result, the VOR/DME navigation system provided the means for successful navigation within the United States.

Some airborne VOR/DME navigation units can provide RNAV capability, while others cannot. A VOR-only unit is limited to a non-RNAV application, while single and multiple VOR/DME units can be designed for either non-RNAV or RNAV operations. The RNAV capability adds to the cost.

A multiple VOR/DME RNAV unit that utilizes two VOR/DME navaids (primary and secondary) offers increased automation as well as a substantial improvement in accuracy as a result of dual-DME processing capability. Since RNAV systems are geographically oriented (e.g., referenced to latitude and longitude), VOR/DME RNAV units generally maintain position in terms of latitude and longitude displacement in relation to the coordinates of the reference VORTAC. To provide this capability, a navaid data base is typically provided, containing the latitude and longitude coordinates of all relevant VORTAC navaids. The navaid information is entered into the data base through either preprogrammed memory elements provided by the manufacturer or manual input by the pilot. Access to this data base enables the use of automatic station-selection algorithms, which eliminate the need for both pilot selection of appropriate navaids and input of corresponding navaid frequencies.

2.3.4 GPS

The satellite-based GPS is still in the development stage. Development of GPS for civil aviation applications is motivated by a desire to replace currently existing navigation systems with a single system that can meet the requirements of all users throughout the world. Although no production units are commercially available yet, studies have been performed, based primarily on cost considerations, on the likely configurations and capabilities of airborne GPS receivers. The need to offset the initial high cost associated with introducing new and complex technology will result in minimizing optional capabilities. Consequently, the "low-cost" GPS receiver is projected to have functional capabilities comparable to the lower cost RNAV VOR/DME systems.

2.4 SUMMARY

Table 2-1 summarizes the functions and features generally available in typical 1980 model airborne navigation units. The table should not be interpreted to suggest that a particular navigation unit always provides the features indicated or that features not included could not be accommodated. The differences between the man/machine interfaces of various RNAV units primarily reflect marketing decisions on the part of the manufacturers. There is no technical impediment to providing all navigation units with the same level of capability in terms of the man/machine interface. In fact, as the market potential for the various types of navigation system units becomes more obvious, the features of these units become more comparable.

Table 2-1. SUMMARY OF TYPICAL FEATURES OF AVAILABLE AIRBORNE NAVIGATION UNITS

Unit Feature	Non-RNAV	RNAV			
	VOR/DME	VOR/DME	Loran-C	Omega	GPS
Inputs					
Flight Planning:					
By latitude/longitude waypoints	-	-	X	X	X
By place/bearing/ distance waypoints	-	X	X	X	X
By navaid alpha designators	-	X	-	X	-
By desired heading:					
Magnetic	TO VORTAC only	X	-	X	-
True		-	-	-	-
By in-flight updating	X	X	X	X	X
Flight Information:					
Current position	-	-	X	X	X
Time (GMT)	-	-	-	X	X
Date	-	-	-	X	X
Magnetic variation:					
Manual	-	-	X	X	X
Automatic prestored	-	-	-	X	-
Actual heading:					
Manual	-	-	-	X	-
Automatic sensor	-	X	-	X	-
True airspeed:					
Manual	-	-	-	X	-
Automatic sensor	-	-	-	X	-
Station Selection/ Deselection:					
Automatic	-	X	X	X	X
Manual	X	X	X	X	X
Operating Modes					
Navigation:					
Direct to:					
Great circle	-	X	X	X	X
Rhumb line	X	X	-	-	-
Leg change:					
Manual	X	X	X	X	X
Automatic	-	X	X	X	X

(continued)

Table 2-1. (continued)

Unit Feature	Non-RNAV		RNAV		
	VOR/DME	VOR/DME	Loran-C	Omega	GPS
Operating Modes (continued)					
Navigation (continued):					
Parallel Offset	-	X	X	X	-
Dead reckoning:					
With sensor updates (e.g., TAS, HDG)	-	-	-	X	-
Without sensor up- dates	-	-	X	X	-
Autopilot Coupling:					
Heading hold	-	-	-	-	-
Track hold	-	X	-	X	X
Turn anticipation	-	X	-	X	X
Display Parameters					
Current Position:					
Latitude/longitude	-	-	X	X	X
Bearing/distance to or from stored waypoint	-	X	X	X	X
Bearing/distance from signal source	X	X	-	-	-
Time to waypoint	-	X	X	X	X
Current Heading:					
Magnetic	-	-	-	X	-
True	-	-	-	X	-
Desired	-	-	-	X	-
Actual	-	-	-	-	-
Deviation	-	-	-	-	-
Drift angle	-	-	-	X	-
Current Track:					
Desired angle	To VORTAC only	X	X	X	X
Actual angle	To VORTAC only	X	X	X	X
Angle error	To VORTAC only	X	X	X	X
Cross-track deviation	X	X	X	X	X
Ground speed	-	X	X	X	X
Atmospheric Conditions:					
Wind speed	-	-	-	X	-
Wind direction	-	-	-	X	-

(continued)

Table 2-1. (continued)

Unit Feature	Non-RNAV		RNAV		
	VOR/DME	VOR/DME	Loran-C	Omega	GPS
Display Parameters (continued)					
Warnings and Indications:					
Operator error	-	-	X	X	*
Malfunction	X	X	X	X	X
Approaching or missed waypoint	X	X	X	X	*
Input/Output (I/O) Interfaces					
Directional Gyro	-	X	-	X	-
True air speed indicator	-	-	-	-	-
Course deviation indicator	X	X	X	X	*
Autopilot	-	X	X	X	*
Data bus, data link	-	X	X	X	*
Flight management computer	-	X	X	X	X
Mechanical Characteristics					
Receiver/Processor Unit (RPU):					
Weight (pounds)	VOR: 3; DME: 5		11.0	11.0	26.0
Volume (cubic feet)	0.1 0.1		0.3	0.4	0.7
Control/Display Unit (CDU):					
Weight (pounds)	Integrated		0.4	5.0	4.0
Volume (cubic feet)	{ in RPU		0.1	0.1	0.1
Cost Range (\$ thousands)	VOR: 1 to 7; DME: 3 to 10	2 to 60	10 to 30	20 to 40	5 to 15
*Insufficient data					
The characteristics of the following units were studied so that the above summary of features of typical navigation systems could be compiled:					
Non-RNAV VOR/DME: Garret AIRNAV RNAV VOR/DME: Collins ANS-31, ANS-351 Bendix NP-2041A King KNR-665A, KNS-80 Foster AirData VNAV-541, AD-611 J.E.T. DAC-2000 Loran-C: Teledyne TDL-711, TDS-424					
Omega: Litton LTN-211 Norden Omega ONS-VII Global Nav GNS-500A Series 2 Collins LRN-80, LRN-85 GPS: Design Studies					

CHAPTER THREE

PERFORMANCE REQUIREMENTS OF NAVIGATION SYSTEMS

3.1 OVERVIEW

The process of selecting a candidate navigation system or a particular navigation system mix for adoption as the United States standard involves a series of comparisons. The essential question to be answered is: which candidate system(s) can provide a level of navigation capability that surpasses all others? The comparison cannot be based on a singular issue such as system accuracy, however. Considerations that must be taken into account are:

- Technical
- Operational
- Institutional
- Economic

Technical considerations are primarily concerned with integrity, reliability, coverage, and accuracy; the means of achieving accuracy is an operational issue. Both technical and operational considerations are related to the environment in which the navigation system will be used. The airspace environment has been divided into two basic phases of air navigation:

- Approach/landing
- En route/terminal

The approach/landing phase includes flight operations generally conducted within 10 nm of the runway in preparation for touchdown. Two categories of approach are defined within this phase: nonprecision and precision.

The en route/terminal phase of flight is divided into categories defined by the following particular geographic areas and operating environments:

- Oceanic en route
- Domestic en route
- Terminal

- Remote areas
- Helicopter operations

Institutional considerations are concerned primarily with the effects and resolution of political issues such as international standardization; distribution of costs; and system ownership, control, operation, and maintenance. Economic considerations include the initial investment; operating, maintenance, and replacement costs; and amortization of the capital investment.

3.2 TECHNICAL CONSIDERATIONS

The system-use accuracy necessary to meet current route requirements is summarized in Table 3-1, which is taken directly from Volume II of the July 1980 *Federal Radionavigation Plan* (FRP). "System-use accuracy" is defined by ICAO to be the square root of the sum of the squares (root sum square [RSS]) of the following error contributions:

- Ground station error
- Airborne receiver error
- Display system error
- Flight technical error

System-use accuracy is a measure of the ability of a navigation system to remain within a specified distance (route width) from a desired point (track). This accuracy is usually expressed in terms of a probability that deviation will be less than some stated magnitude of error. Different terms are used to define error, depending on the application. The terms "standard deviation" and "root mean square" are equivalent when they refer to one-dimensional zero-mean errors. Navigation errors typically have components in at least two dimensions -- along-track and cross-track. Terms commonly used in referring to two-dimensional navigation accuracy include circular error probability (CEP), standard deviation, and drms.

CEP defines the radius of a circle for which there is a 50 percent probability that all position measurements will be inside. Standard deviation, or sigma (σ), in a two-dimensional analysis involves a radial rather than a linear distribution of errors. Numerically, 1σ corresponds to 39.95 percent ($Z = 86.47$ percent) of a circular distribution, whereas it corresponds to 68.27 percent ($2\sigma = 95.45$ percent) of a linear distribution. Reference to a circular standard deviation is meaningful only when the error figure, whose orthogonal axes are defined by one-dimensional errors (referred to as σ_x and σ_y), is a circle, which results only when $\sigma_x = \sigma_y$. Since σ_x and σ_y are generally not equal, reference to a position accuracy of 2σ can cause confusion as to whether the number describes the 86 percent two-dimensional probability circle or the 95 percent one-dimensional probabilities for each error axis.

Table 3-1. CONTROLLED AIRSPACE NAVIGATION ACCURACY TO
MEET CURRENT REQUIREMENTS

Phase	Sub-Phase	Altitude (Flight Level)	Traffic Density	Route Width (NM)	Accuracy 2 drms (meters)
En Route/ Terminal	Oceanic	FL 275 to 400	Normal	60	12.6 NM(1)
	Domestic	FL 180 to 600	Low	16	2000
			Normal	8	1000
		500 - 18,000 ft.	High	8	1000
	Terminal	500 - 18,000 ft.	High	4	500
	Remote	500 - 60,000 ft.	Low	8 to 20	1000 to 4000
	Helicopter Operations	500 - 5000 ft.	Low (Off Shore)	Not Determined	1000 to 2000
		500 - 3000 ft.	High (Land)	4	500
	Non-Precision Approach and Landing	250 to 3000 ft. above Surface	Normal	2	100
	Precision	Cat I	100 to 3000 ft. above Surface	+ 9.1 meters (2) at 100 ft. above Surface	+ 3 meters (3) at 100 ft. above Surface
Source: Federal Radionavigation Plan, Reference 22.	Cat II	50 to 3000 ft. above Surface	Normal		
	Cat III	0 to 3000 ft. above Surface	Normal		
				+ 4.1 meters at Surface	+ 0.5 meters at Surface

(1) The distribution of this error is detailed in the "Report of the Limited North Atlantic Regional Air Navigation Meeting," dated 1976; ICAO Montreal Canada

(2) This column is lateral position 2 sigma accuracy in meters for Precision Approach and Landing

(3) This column is vertical position 2 sigma accuracy in meters for Precision Approach and Landing

The concept of root-mean-square error or radial error (drms) is introduced to give a single measure that will account for variations in both σ_x and σ_y that generate an error ellipse rather than a circle. One drms is defined as the radius of a probability circle, with the magnitude of the radius the RSS of the one-dimensional 1 σ error components along the major and minor axes (σ_x and σ_y) of the error ellipse. The major drawback of this measure is that the value of probability associated with a fixed value of drms varies with the eccentricity of the error ellipse. Use of 2 σ error components results in the computation of a 2 drms value. The 2 drms variation in probability is small (0.954 to 0.982).

Just as navigation errors can be expressed in different terms, navigation accuracy can be expressed in terms such as the following:

- Predictable accuracy. Also referred to as absolute accuracy, it is the accuracy associated with predicting position with respect to geographical coordinates.
- Relative accuracy. The accuracy with which a user can measure relative position with respect to another user of the same navigation system at the same time.
- Repeatable accuracy. The accuracy with which a user can return to a position whose coordinates have been measured previously with the same navigation system.

While accuracy defines the difference between a measurement value and a reference value, precision defines the degree of refinement to which the value can be expressed.

System-use accuracy corresponds to predictable, or absolute, accuracy in a statistical sense. The interpretation of the 2 drms accuracy values (shown in Table 3-1) is that the along-track and cross-track error components cannot combine to yield a result exceeding the value given for 95 percent of the measurements taken.

Table 3-1 does not reflect the system-use accuracy requirements for area navigation systems. FAA Advisory Circular (AC) 90-45A provides the requirements for approval of area navigation systems for use in the United States National Airspace System (NAS). Figure 3-1, reproduced from AC 90-45A, presents the maximum allowable errors for VOR/DME-based area navigation systems. The figure indicates allowable cross-track and along-track errors as a function of distance from the VORTAC reference. Rather than defining distance from the VORTAC as radial distance, Figure 3-1 resolves the distance into two orthogonal components (illustrated at the bottom of the figure). The radial distance is the hypotenuse of the right triangle thus formed.

As an example of how Figure 3-1 is used, consider an aircraft flying along a flight path that is offset from the VORTAC by 30 nm. This offset distance, sometimes referred to as the abeam distance, is defined as the perpendicular distance from the VORTAC to the flight path. At the time of interest, assume that the aircraft is 50 nm from the abeam point, from which

PERPENDICULAR DIST TO TANGENT POINT

	0	5	10	15	20	25	30	35	40	50	60	70	80	90	100	110	120	130	150	100	
0(x trk)	.0	.8	1.1	1.3	1.6	1.9	2.2	2.5	3.1	3.7	4.4	5.0	5.6	6.2	6.8	7.4	8.1	9.3	14.6		
(alg trk)	.7	.7	.7	.8	.9	1.0	1.2	1.3	1.6	1.9	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.5	6.0		
1(x trk)	.7	.7	.6	1.1	1.4	1.6	1.9	2.2	2.5	3.2	3.8	4.4	5.0	5.6	6.2	6.9	7.5	8.1	9.3	12.4	
(alg trk)	.6	.7	.8	1.8	1.9	1.0	1.1	1.2	1.4	1.6	1.9	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.6	6.1	
2(x trk)	.7	.8	.7	1.1	1.6	1.7	2.0	2.3	2.6	3.2	3.8	4.4	5.0	5.6	6.2	6.9	7.5	8.1	9.3	12.4	
(alg trk)	.8	.8	.9	1.1	1.6	1.7	2.0	2.3	2.6	3.2	3.8	4.4	5.0	5.6	6.2	6.9	7.5	8.1	9.3	12.4	
3(x trk)	.7	.8	1.1	1.1	1.2	1.2	1.3	1.4	1.5	1.7	2.0	2.3	2.6	2.9	3.1	3.4	3.7	4.0	4.6	6.1	
(alg trk)	1.1	1.1	1.1	1.2	1.2	1.3	1.3	1.4	1.5	1.6	1.7	1.8	2.1	2.4	2.7	3.0	3.2	3.5	3.8	6.2	
4(x trk)	.8	.9	1.0	1.2	1.4	1.6	1.7	2.0	2.1	2.6	3.2	3.8	4.4	5.0	5.6	6.2	6.9	7.5	8.1	9.3	12.4
(alg trk)	1.3	1.4	1.4	1.4	1.5	1.6	1.7	1.8	1.9	2.1	2.3	2.6	2.8	3.1	3.1	3.6	3.9	4.2	4.8	6.2	
5(x trk)	.9	1.0	1.1	1.3	1.3	1.8	1.8	2.1	2.4	2.7	3.2	3.9	4.5	5.1	5.7	6.3	6.9	7.5	8.1	9.4	12.2
(alg trk)	1.6	1.6	1.7	1.7	1.8	1.9	2.0	2.1	2.1	2.3	2.5	2.7	3.0	3.6	4.0	4.3	4.9	6.3			
6(x trk)	1.0	1.1	1.2	1.4	1.6	1.7	1.9	2.2	2.3	2.7	3.1	3.9	4.5	5.1	5.7	6.3	6.9	7.6	8.2	9.4	12.5
(alg trk)	2.0	2.0	2.1	2.1	2.2	2.2	2.3	2.3	2.5	2.5	2.7	3.2	3.4	3.7	3.9	4.2	4.5	5.0	6.4		
7(x trk)	1.1	1.2	1.4	1.5	1.6	1.8	2.0	2.3	2.5	2.8	3.6	4.0	4.6	5.2	5.8	6.4	7.0	8.2	9.4	12.5	
(alg trk)	2.2	2.2	2.3	2.3	2.3	2.4	2.5	2.5	2.6	2.8	3.0	3.2	3.4	3.6	3.9	4.1	4.4	4.6	5.2	6.5	
8(x trk)	1.3	1.4	1.5	1.6	1.7	1.8	2.0	2.3	2.5	2.8	3.6	4.0	4.6	5.2	5.8	6.4	7.0	7.6	8.2	9.5	12.5
(alg trk)	2.5	2.5	2.6	2.6	2.7	2.7	2.8	2.9	3.0	3.2	3.4	3.6	3.8	4.0	4.3	4.5	4.8	5.3	6.7		
9(x trk)	1.6	1.8	1.7	1.9	2.1	2.3	2.5	2.8	3.0	3.6	4.1	4.7	5.3	5.9	6.5	7.1	7.7	8.3	9.5	12.6	
(alg trk)	3.1	3.2	3.2	3.2	3.2	3.3	3.3	3.4	3.4	3.6	3.7	3.9	4.1	4.3	4.5	4.7	4.9	5.2	5.7	7.0	
10(x trk)	1.9	1.9	2.0	2.1	2.3	2.3	2.7	3.0	3.0	3.2	3.7	4.3	4.8	5.4	6.0	6.6	7.2	8.4	9.0	12.6	
(alg trk)	3.7	3.8	3.8	3.8	3.9	3.9	4.0	4.0	4.0	4.1	4.3	4.4	4.6	4.8	5.0	5.2	5.4	5.6	6.0	7.3	
11(x trk)	2.2	2.2	2.3	2.4	2.6	2.7	2.9	3.2	3.4	3.9	4.4	5.0	5.5	5.9	6.1	6.7	7.3	8.5	9.7	12.7	
(alg trk)	4.6	4.6	4.6	4.6	4.6	4.6	4.5	4.6	4.6	4.7	4.8	5.0	5.1	5.3	5.5	5.6	5.8	6.0	6.5	7.7	
12(x trk)	2.5	2.5	2.6	2.7	2.8	3.0	3.2	3.4	3.6	4.1	4.6	5.1	5.7	6.2	6.8	7.4	8.0	8.6	9.8	12.8	
(alg trk)	5.0	5.0	5.0	5.0	5.1	5.1	5.2	5.2	5.3	5.3	5.5	5.7	5.8	6.0	6.2	6.3	6.5	6.9	8.0		
13(x trk)	2.6	2.6	2.9	3.0	3.1	3.2	3.4	3.6	3.8	3.8	4.3	4.8	5.3	6.4	6.9	7.5	8.7	9.9	12.9		
(alg trk)	5.6	5.6	5.6	5.6	5.7	5.7	5.8	5.8	5.9	6.0	6.1	6.2	6.4	6.5	6.7	6.8	7.0	7.4	8.5		
140(x trk)	3.0	3.1	3.1	3.2	3.4	3.5	3.7	3.9	4.0	4.5	5.0	5.5	5.9	6.0	6.5	6.7	7.1	7.6	8.9	10.0	12.9
(alg trk)	6.2	6.2	6.2	6.2	6.3	6.3	6.3	6.4	6.4	6.5	6.6	6.7	6.8	6.9	7.2	7.4	7.5	7.9	8.9		
150(x trk)	3.3	3.6	3.6	3.5	3.6	3.6	3.9	4.1	4.3	4.7	5.2	5.6	6.2	6.7	7.2	7.8	8.3	8.9	10.1	13.0	
(alg trk)	6.8	6.8	6.9	6.9	6.9	6.9	7.0	7.0	7.1	7.3	7.4	7.5	7.6	7.8	7.9	8.1	8.4	9.4			
160(x trk)	3.6	3.7	3.7	3.8	3.9	4.0	4.2	4.4	4.5	4.9	5.4	5.8	6.2	6.8	7.4	7.9	8.5	9.0	10.2	13.1	
(alg trk)	7.6	7.7	7.7	7.8	7.8	7.9	7.9	7.9	7.9	8.0	8.1	8.2	8.3	8.5	8.6	9.0	9.6	10.3			
170(x trk)	3.9	4.0	4.0	4.1	4.2	4.3	4.5	4.6	4.8	5.2	5.6	6.0	6.5	7.0	7.5	8.1	8.6	9.2	10.3	13.2	
(alg trk)	8.1	8.1	8.1	8.1	8.1	8.1	8.2	8.2	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9.0	9.5	10.4		
180(x trk)	4.2	4.3	4.3	4.4	4.5	4.6	4.7	4.9	5.0	5.3	5.6	6.3	6.7	7.2	7.7	8.2	8.4	9.3	10.5	13.3	
(alg trk)	8.7	8.7	8.7	8.7	8.7	8.8	8.8	8.8	8.8	8.9	9.0	9.1	9.2	9.3	9.4	9.6	9.7	10.0	10.9		
190(x trk)	4.5	4.6	4.6	4.7	4.8	4.9	5.0	5.2	5.3	5.7	6.5	6.9	7.4	7.9	8.4	9.0	9.5	10.6	13.5		
(alg trk)	9.1	9.3	9.3	9.4	9.4	9.4	9.5	9.5	9.5	9.6	9.7	9.8	9.9	10.1	10.2	10.3	10.6	11.4			

TO FIND THE CROSS-TRACK AND ALONG-TRACK ELECTRONIC SYSTEM ERROR (LESS PILOTAGE) AT A POINT, ENTER TABLE WITH PERPENDICULAR DISTANCE AND DISTANCE ALONG TRACK FROM TANGENT POINT, i.e., when the Perp Dist is 30 and the along-track dist is 50, the cross-track error is ± 3.3 NM and the along-track error is 2.5 NM.

Tangent Pt

ALONG TRACK DIST



ERROR ELEMENTS

GROUND	
VOR	1.0
DME	0.1 NM
AIRBORNE	
VOR	3.0
DME	3% or 0.5 NM
RNAV SYSTEM	0.5 NM
PILOT	ZERO

Source: FAA Advisory Circular 90-45A, Reference 23.

Figure 3-1. VOR/DME/TACAN STATION REFERENCED AREA NAVIGATION ERROR TABLE (95% PROBABILITY)

the abeam distance to the VORTAC is measured. The block drawn in Figure 3-1 indicates the allowable error associated with an abeam distance of 30 nm and an along-track distance of 50 nm from the abeam point: ± 3.3 nm cross-track and 2.5 nm along-track. The allowable error for any distance can be found in this manner. Table 3-2 summarizes the requirements specified for non-VOR/DME-based two-dimensional (2-D) RNAV systems. All error values correspond to 95 percent confidence levels.

Table 3-2. ALLOWABLE ERROR BUDGETS FOR NON-VOR/DME-BASED RNAV SYSTEMS (NAUTICAL MILES)

Type of Error	Flight Phase Allowable Error Budgets					
	En Route		Terminal		Nonprecision Approach	
	Cross-Track	Along-Track	Cross-Track	Along-Track	Cross-Track	Along-Track
Equipment	1.50	1.50	1.12	1.10	0.33	0.30
Flight Technical	2.00	--	1.00	--	0.50	--
Total System Error (RSS)	2.50	1.50	1.50	1.10	0.60	0.30

3.3 OPERATIONAL CONSIDERATIONS

The following requirements are taken verbatim from Volume II of the FRP as listed in section 2.1.1 therein, "Aviation Requirements."

- A. The system must be suitable for use in all aircraft types which may require the service without unduly limiting the performance characteristics of those aircraft types, e.g., maneuverability and fuel economy.
- B. The system must be safe, reliable, available and capable of providing service over all the used airspace of the world, regardless of time, weather, terrain, and propagation anomalies.
- C. The overall integrity of the system, including the presentation of information in the cockpit, shall be as near 100 percent as is achievable and to the extent feasible should provide flight deck warnings in the event of failure, malfunction, or interruption.
- D. The system must have a capability of recovering from a temporary loss of signal in such a manner that the correct current position will be indicated without the need for complete resetting.
- E. The system must automatically present to the pilot adequate warning in the case of malfunctioning of either the airborne or source portions of the system, and assure ready identification of erroneous

information which may result from a malfunctioning of the whole system or incorrect setting.

- F. The system must provide in itself maximum practicable protection against the possibility of input blunder or misinterpretation of output data.
- G. The system must provide adequate means for the pilot to check the accuracy of airborne equipment.
- H. The system must employ navigational information source equipment which automatically and radically changes the character of its indication in case a divergence from accuracy occurs outside safe tolerance.
- I. The system must employ navigational information source equipment which provides immediate and positive indication of malfunction.
- J. The navigational information provided by the system must be free from unresolved ambiguities of operational significance.
- K. Any source-referenced component of the total navigation system shall be capable of providing navigational information simultaneously and instantaneously to all aircraft which require it within the area of coverage.
- L. The navigation system must be capable, in conjunction with other flight instruments, of providing to the pilot in convenient, natural, and rapidly assimilable form in all circumstances, and the appropriate phases of flight, information directly applicable to the handling of the aircraft, for the purpose of:
 - 1. Continuous track guidance.
 - 2. Continuous determination of distance along track.
 - 3. Continuous determination of position of aircraft, as resolved by the navigation system.
 - 4. Position reporting.
 - 5. Manual or automatic flight.The system shall also provide for input and utilization of the above in conveniently operable form; and must permit design of indicators and controls which can be directly interpreted or operated by the pilot at his normal station aboard the aircraft.
- M. The system must be capable of being integrated into the overall ATC, communications, and navigation system.

- N. The system should be capable of integration with all phases of flight, including the precision approach and landing system.
- O. The system must permit the pilot to determine the position of the aircraft with an accuracy and frequency such as to ensure that the separation minima used can be maintained at all times, execute accurately the required holding and approach patterns, and to maintain the aircraft within the area allotted to the procedures.
- P. The system must permit the establishment and the servicing of any practical, defined, route structure for the appropriate phases of flight as required.
- Q. The system must have sufficient flexibility to permit changes to be made to the air-route structure and siting of holding patterns without imposing unreasonable inconvenience or cost to the providers and the users of the system.
- R. The system must be capable of providing the information necessary to permit maximum utilization of airports and airspace.
- S. The system must be cost-effective to both government and users.
- T. The system must employ equipment such as to minimize susceptibility to interference from adjacent radio-electronic equipment and shall not cause objectionable interference to any associated or adjacent radio-electronic equipment installation in aircraft or on the ground.
- U. The system must be free from signal fades or signal-to-signal plus noise ratios below which the system cannot operate in the operating area.
- V. The system avionics must be comprised of the minimum number of elements which are simple enough to meet, economically and practically, the most elementary requirements, yet be capable of meeting, by the addition of suitable elements, the most complex requirements.
- W. The system must be capable of furnishing reduced service to aircraft with limited or partially inoperative equipment.
- X. The system must be capable of integration with the flight control system of the aircraft to provide automatic tracking.

No one set of aviation navigation operational requirements, even though they meet the basic requirement for safety, can adequately reflect the many different combinations of operating conditions encountered in various parts of the world, in that the requirements applicable to the most exacting region may be extravagant when applied to others.

3.4 INSTITUTIONAL CONSIDERATIONS

In addition to the technical and operational considerations discussed previously, a number of institutional issues will play a major role in determining which mix of navigation systems will be used in the future. Although it is not within the scope of this study to evaluate in detail the influence that institutional issues will have on the selection process, some factors are considered to be significant enough to be discussed briefly.

3.4.1 International Standardization

The United States (and consequently the FAA) is an active participant in the international aviation community as represented by ICAO and other organizations. One function of ICAO is to facilitate international aeronautical activity and cooperation through coordination and recommendation of standardized equipment and procedures. In 1959, ICAO approved VOR/DME as the international standard for aeronautical navigation through 1984. Of the 2,609 VOR/DME facilities that currently exist worldwide, 1,152 are registered in the ICAO Air Navigation Plans as international navigation aids. An additional 466 international facilities are scheduled for installation according to these plans. Consequently, there is strong international sentiment for maintaining VOR/DME as the international standard at least through 1995 -- a proposal that ICAO is expected to formally adopt soon. Past experience has demonstrated that a particular type of navigation aid (e.g., Loran-A) continues to be used for 15 years or more after its official protection ceases. This being the case, it could be assumed that VOR/DME will continue to be used extensively worldwide into the year 2010.

ICAO has no plans, formal or informal, to endorse either Loran-C, Omega, or GPS as an alternate or replacement international standard aeronautical navigation aid. Loran-C coverage areas are unlikely to extend beyond what is currently planned, which still excludes the Southern Hemisphere. Omega already provides essentially worldwide coverage, and the necessary international agreements for maintenance and operation of the transmitting stations have been negotiated and accepted. GPS is currently a United States military-sponsored satellite navigation system; its implementation does not require international cooperation other than for frequency allocation.

One of the central issues concerning international, and frequently domestic, endorsement of a particular navigation system standard involves the responsibility of control. The organization that controls the system can theoretically limit access to that system. Because VOR/DME, Loran-C,

and, to some extent, Omega are systems where the control responsibility is distributed among many nations and organizations, they will likely remain available to all users of all nations. GPS, however, is a system that inherently requires centralized control. This control will have to be vested in either a single country or an international organization. If the former occurs, international support is likely to be difficult to obtain. If the latter is the case, the system may become unappealing to its most prominent supporters in the United States, and its acceptance may be delayed while institutional arrangements are prepared for international GPS management.

Intertwined closely with the issue of system control is allocation of operation and maintenance responsibility and cost. The distributed regional systems such as VOR/DME and Loran-C are well suited for the international environment, since the using, controlling, operating, and maintenance functions are typically the combined responsibilities of the country in which the facilities are located. Omega also presents no difficulties in this context, because the operational and maintenance considerations have already been agreed to by treaty. GPS, however, is likely to encounter significant institutional difficulties in allocation of operation and maintenance responsibility and cost.

3.4.2 Transitional Impact

International governments as well as the various user communities have significant capital investments in the existing VOR/DME-based navigation system. These investments must be protected over an extended period of time while any new system is being phased in to allow for full amortization of the old system. The institutional difficulties associated with effectively maintaining standards for two navigation systems over a period of possibly 15 to 20 years may be so cumbersome and uneconomical as to force retention of the VOR/DME system until the successor system can have a guaranteed useful life of at least 30 to 50 years.

3.4.3 Special Interest Groups

The acceptability and desirability of any single navigation system or combination of systems will ultimately be determined by the user community, either directly or indirectly. For example, the airlines provide the impetus for the application of Omega to en route navigation in the continental United States, offshore oil prospectors generate the market for Loran-C, and private pilots continue to provide demand for VOR/DME. User preferences are evidenced through public statements of trade associations and, more importantly, through equipment purchases.

3.5 ECONOMIC CONSIDERATIONS

Both the Government, as the provider of navigation capability, and the user, as the purchaser of equipment for aircraft, are concerned about the life-cycle cost of the navigation system or combination of systems selected for future user. Consequently, numerous cost analyses have been performed

for alternative navigation scenarios. The following two reports have quantified the total Government and user life-cycle costs of various navigation system combinations:

- *Economic Requirements Analysis of Civil Air Navigation Alternatives*, Reference 29
- *Economic Analysis of Future Civil Air Navigation Systems*, Reference 30

In broad terms, these studies have concluded that neither Loran-C, GPS, nor Omega can compete in cost with the single VOR receiver for low-budget aviation. However, if area navigation becomes the standard of the air traffic control system, the specific combination of systems used will have little relative cost impact as long as the existing user capital investment in VOR/DME is utilized concurrently with any newly introduced system (e.g., VOR/DME with Loran-C or VOR/DME with GPS). If the existing VOR/DME network is discarded in favor of a totally new navigation concept such as GPS, the cost to retrofit all existing aircraft with the new navigation equipment will exact a significant cost penalty from the users, as compared with the other approaches. The quantitative conclusions of these two reports are summarized in Table 3-3.

Table 3-3. LIFE-CYCLE-COST COMPARISONS OF NAVIGATION SYSTEMS

Navigation System(s) Used	Total Life-Cycle Cost to U.S. Government and Users Normalized to Baseline	
	SCI*	Mitre Corp.**
VOR/DME (RNAV not required) in U.S.; Omega for global navigation.	1.00 (baseline)	1.00 (baseline)
VOR/DME with Loran-C (RNAV required) in U.S.; Omega for global navigation.	Not Studied	1.13
VOR without DME (RNAV not required) in U.S.; GPS for RNAV and global navigation.	1.20	1.08
RNAV Loran-C in U.S.; Omega for global navigation.	1.20	1.24
RNAV GPS -- both in U.S. and for global navigation.	1.40	1.40

**Economic Requirements Analysis of Civil Air Navigation Alternatives*, Systems Control, Inc., Reference 29.
***Economic Analysis of Future Civil Air Navigation Systems*, Mitre Corp., Reference 30.

CHAPTER FOUR

TECHNICAL EVALUATION OF NAVIGATION SYSTEMS

4.1 OVERVIEW

The technical performance capability of a navigation system is strongly influenced by the properties of the received signal as well as the techniques used by the airborne receiver in processing the signals. Significant signal properties include stability, coverage, and availability. Signal acquisition and tracking continuity depend on both signal and receiver characteristics.

Accuracy of hyperbolic radionavigation systems such as Loran-C and Omega is primarily dependent on the accuracy and precision with which time or phase differences can be measured. When ranging techniques are used for Loran-C and Omega navigation, achievable accuracy is a function of the time synchronization of the transmitters, user clock biases, accuracy of propagation modeling, and the geometry of the user's position in relation to the transmitting stations.

Accuracy of VOR/DME is primarily influenced by the inaccuracies of VOR. The most dominant VOR errors are caused by multipath effects. Multipath signals are caused by reflecting objects near the transmitter that scatter the original signal. These multipath signals create distortions in the desired signal resulting from different paths being simultaneously traveled by the signal between transmitter and receiver. The result is scalloping in the VOR bearing indications.

Accuracy of the GPS concept, a space-based radionavigation system, depends on accurate and continuous knowledge of the spatial position of each satellite in the system with respect to time and distance from the user.

Although compliance of a navigation system to technical performance requirements such as accuracy is necessary, it is not a sufficient condition for acceptability. Also important are operational considerations relating to the ability of the system to interact with the pilot and ATC to meet and maintain operational standards of safety and accuracy. The summary of features of typical navigation units presented in Table 2-1 provides an indication of the operational compatibility of various navigation systems in terms of the system/user interface. The following sections present the technical capabilities of each system in terms of an error budget.

4.2 ERROR BUDGET FOR LORAN-C

The error budget for Loran-C is broadly divisible into five categories as follows:

- Transmitter errors
- Signal detection errors
- Receiver clock errors
- Signal propagation variations
- Position fix calculation errors

Table 4-1 presents a summary of the impact of specific errors on the navigational accuracy of various Loran-C system uses. As can be seen from the table, inaccurate prediction of signal propagation variations is the dominant contributor to the total RSS system accuracy, excluding flight technical error. Although it may appear that hyperbolic navigation is more accurate than either rho-rho or rho-rho-rho navigation, that is not the case in an operational environment. When user distance from a Loran-C baseline is large in relation to the length of the baseline, the user is in a high GDOP situation. The relatively short baselines of Loran-C chains result in typical GDOPs of 2 to 4 when hyperbolic navigation is used. Use of rho-rho or rho-rho-rho techniques effectively eliminates GDOP considerations. Each error source is discussed in the following sections.

4.2.1 Transmitter Errors

Loran-C receivers presume that the received signal originated at a particular instant in time at a specific location. Jitters in the timing of the Loran-C pulse or errors in transmitter location are interpreted by the receiver as variations in signal propagation time. These propagation variations in turn directly translate into position fix errors.

4.2.1.1 Timing Error

Loran-C transmitters are synchronized with each other via extremely accurate internal atomic clocks and information from various monitor stations. The most critical types of timing errors include lack of proper signal phase or envelope coherence among stations, as follows:

- Master station timing error
- Master-slave timing error
- Slave-slave timing error
- Chain-chain timing error

Table 4-1. POSITION ERROR BUDGET SUMMARY FOR LORAN-C

Error Source	Impact of Error (\pm nm) on Navigation System Use		
	Hyperbolic	Rho-Rho	Rho-Rho-Rho
Transmitter Errors:			
Timing Location	0.03 8×10^{-4}	0.03 8×10^{-4}	0.03 8×10^{-4}
Signal Detection Errors:			
Zero crossing detection	2.5×10^{-3}	2.5×10^{-3}	2.5×10^{-3}
Phase comparison quantization	3×10^{-3}	3×10^{-3}	3×10^{-3}
Cycle jump*	1.65	1.65	1.65
Receiver Clock Errors:**			
Initialization Drift	Negligible 2.5×10^{-6}	0.06 3×10^{-3} †	0.06 2.5×10^{-6}
Signal Propagation Variations:			
Prediction Random*	0.06 0.01	0.06 0.01	0.06 0.01
Position Fix Calculation Errors:*			
Earth model Dead reckoning	0.2 5.5×10^{-4}	0.2 5.5×10^{-4}	0.2 5.5×10^{-4}
Total System Position Error (RSS 2 drms):			
GDOP = 1	0.07	0.09	0.09
GDOP = 4	0.28	--	--

*Excluded from RSS calculation.
**Quartz clock unless otherwise noted.
†Rubidium clock or better.

The United States Coast Guard, which operates the Loran-C system in the United States, has specified the following four operational modes for transmitters:^{*}

- (1) Optimum - achieved 95% of the time; full power - timing precision of ± 40 n seconds;
- (2) Precision - achieved 97% of the time; half power - timing precision of ± 40 n seconds;
- (3) Enhanced - achieved 98.6% of the time; full power - timing precision of ± 200 n seconds; and
- (4) Standard - achieved 99.7% of the time; half power - timing precision of ± 200 n seconds.

For this discussion, the standard operating mode is used to determine transmitter errors. Therefore, the sum of all timing errors associated with transmitters is assumed to be less than ± 200 nanoseconds (ns), corresponding with a propagation distance error of ± 0.03 nm (± 55.6 meters).

4.2.1.2 Location Error

Published locations of Loran-C stations are accurate to 0.1 arc second. Any variation of actual signal origin from these published position coordinates is reflected directly into an erroneous range measurement from the station. An accuracy of 0.1 arc second is the same as an error of ± 0.05 arc second, corresponding with a position fix error of $\pm 8 \times 10^{-4}$ nm (± 1.5 meters).

4.2.2 Signal Detection Errors

Each Loran-C pulse contains 20 cycles of radio frequency (RF) energy and exhibits a slowly rising and decaying amplitude envelope shaped much like a teardrop. The energy contained in the first two cycles of the pulse is insufficient for a good signal-to-noise ratio measurement. The fourth cycle is likely to be contaminated by sky waves. Therefore, receivers typically are designed to measure pulse arrival at the third cycle. The most accurate technique for measuring time of signal arrival is to detect the third pulse zero crossing and compare that time to a local oscillator. The exact time is measured in terms of a phase relationship between the local oscillator and the received signal. The following subsections describe the three sources of error that contribute to Loran-C position uncertainty.

4.2.2.1 Zero Crossing Detection Error

The zero crossing is derived by comparing the squared-off Loran RF signal with the local oscillator clock. The squared-off Loran signal is derived through a means such as use of a saturating amplifier. There is

*Reprinted verbatim from *A Comparative Analysis of Area Navigation Systems in General Aviation*, Reference 28.

approximately 1 degree of error associated with identifying the precise moment of zero crossing. This 1-degree error in a 100 kHz signal corresponds with 0.03 microsecond, or a propagation distance error of $\pm 2.5 \times 10^{-3}$ nm (± 4.6 meters).

4.2.2.2 Phase Comparison Quantization Error

The phase difference between the local oscillator and the received Loran pulse is usually measured using a digital counter that runs several times faster than the basic RF carrier rate of 100 kHz. Current engineering designs typically provide resolution of 40 ns (± 20 ns error), corresponding with a propagation distance error of $\pm 3 \times 10^{-3}$ nm (± 5.6 meters).

4.2.2.3 Cycle Jump Error

Under certain atmospheric propagation conditions, differences between the phase and group velocities in the RF signal affect the shape of the Loran-C pulse so that it is distorted by the time it reaches the receiver. This pulse distortion may "fool" the receiver into miscounting the true cycle crossings and thus locking onto the second or fourth cycle of the Loran pulse. This phenomenon is called cycle jump. Most Loran receivers have special circuitry and logic to prevent this from happening and to warn the operator if it does occur. The position error introduced by cycle jump is the equivalent propagation time of one Loran-C cycle, or 10 microseconds, corresponding with a propagation distance error of ± 1.65 nm.

4.2.3 Receiver Clock Errors

There are two types of clock errors. The first is error associated with initial synchronization, and the second is a function of stability.

4.2.3.1 Clock Initialization Error

In the hyperbolic mode, clock initialization errors have minimal effect on position accuracy, because only the time difference between incoming signals is measured, resulting in the cancellation of initialization errors. In the rho-rho mode, initialization errors are significant because they add a constant error to the position fix. The accuracy of the initial clock synchronization is limited by knowledge of the exact distance from the receiver at the time of initialization, knowledge of the propagation characteristics at the time of initialization, and the receiver's signal detection accuracy at the time of initialization. These different types of error are presented in Table 4-2.

In the rho-rho-rho mode, a third Loran station can be used to calculate clock offset. Theoretically, initial clock synchronization errors can be completely eliminated through repeated measurements of position. In reality, however, there is a residue of error dominated by the receiver's signal detection capabilities of $\pm 3 \times 10^{-3}$ nm (± 5.6 meters).

Table 4-2. RECEIVER INITIALIZATION ERRORS

Error Related to:	Derivation	Report Section	Magnitude (\pm nm)
Range from transmitter	Accuracy limit on transmitter and receiver locations is ± 0.05 arc second.	4.2.1.2	8×10^{-4}
Propagation	Errors in prediction.	4.2.4	0.06
Signal detection	Phase comparison quantization.	4.2.2	3×10^{-3}

4.2.3.2 Clock Drift Error

If the local oscillator is unstable and drifts in relation to the transmitter clocks, the airborne system perceives this as a shift in time difference and computes an erroneous position.

In the hyperbolic mode, only short-term clock stability is important. With a quartz crystal clock, drift is about 3×10^{-11} seconds per 0.1-second measurement interval, corresponding with a propagation distance error of $\pm 2.5 \times 10^{-6}$ nm (± 0.005 meters).

In the rho-rho mode, the clock is free-running during each leg of the flight and thus may not be resynchronized for two to six hours. During a six-hour flight, a quartz clock will drift 7.2 microseconds, corresponding with a propagation distance error of ± 0.6 nm. A rubidium clock is more stable and will reduce this error to 3.6×10^{-8} seconds, or $\pm 3 \times 10^{-3}$ nm (± 5.6 meters).

In the rho-rho-rho mode, a third Loran-C station is used to estimate and compensate for the error resulting from clock drift. This readjustment occurs every 0.1 second, as in the hyperbolic mode. Therefore, the effect of drift will be minimal for any high quality clock used in the receiver.

4.2.4 Signal Propagation Variations

4.2.4.1 Prediction Error

The propagation velocity of electromagnetic waves varies slightly as a function of the medium through which the waves are passing. For Loran-C, the characteristics of the medium depend on surface effects and atmospheric conditions. Surface effects are important, because Loran-C receivers derive range information from ground waves traveling along the surface of the earth. Propagation models that assume that the ground waves travel

over seawater will introduce position errors when used over land. The uncertainty associated with determining the correct propagation velocity from the transmitter to the user is referred to as prediction error. Estimates of the magnitude of prediction error are typically around ± 0.4 microsecond, corresponding with a propagation distance error of ± 0.06 nm (± 111.1 meters).

4.2.4.2 Random Error

Many influences on signal propagation cannot be adequately predicted. The impact of these error sources on position accuracy is primarily a function of the limit of signal detection possible as a consequence of noise. The operational limit of most radionavigation systems, including Loran-C, is determined by the signal-to-noise ratio (SNR) in which the receiver must operate. Analyses have shown that the unpredictable error in an excellent SNR environment (1:1) is about 0.05 microsecond, or $\pm 4 \times 10^{-3}$ nm. In a typical SNR environment (1:3), unpredictable errors increase to a value of about 0.14 microsecond, corresponding with a propagation distance error of ± 0.01 nm (± 18.52 meters).

4.2.5 Position Fix Calculation Errors

4.2.5.1 Earth Model

Once the range from the Loran-C transmitter has been determined, the geographical position of the user is computed on the basis of a mathematical model of the earth. Position fix errors resulting from the lack of agreement between earth models can be as great as ± 0.2 nm (± 370.4 meters).

4.2.5.2 Dead Reckoning

Initiation of a maneuver or a sudden change in the wind vector introduces an error rate of 5.5×10^{-3} nm per second (based on an along-track wind change of 20 knots), which decays to zero as the tracking loop of the receiver compensates for the change in dynamics during successive update cycles. Between 0.1-second measurement updates of Loran-C, an error of 5.5×10^{-3} nm per second results in a position fix error of 5.5×10^{-4} nm (± 1.0 meters).

4.3 ERROR BUDGET FOR OMEGA

Errors for Omega are divided into the same five categories as defined for Loran-C:

- Transmitter errors
- Signal detection errors
- Receiver clock error
- Signal propagation variations
- Position fix calculation errors

A summary of the impact of these errors on Omega navigation accuracy is presented in Table 4-3. As can be seen in the table, propagation modeling errors overwhelmingly predominate and limit the overall accuracy of position fixing. The baselines between Omega transmitters are much longer than those for Loran-C; therefore, the typical GDOP associated with Omega hyperbolic navigation is 2, whereas it was 4 with Loran-C. Each error source is discussed in the following sections.

4.3.1 Transmitter Timing Errors

Since the Omega system assumes availability of perfectly synchronized and phase-locked VLF radio transmissions, any jitter will result in an erroneous position fix. The eight Omega transmitters are phase-locked by means of monitor stations and use very accurate atomic clocks at each station for frequency standards. Timing errors between stations are limited to 1 microsecond, corresponding with a propagation distance error of ± 0.08 nm (± 148.2 meters).

4.3.2 Signal Detection Errors

4.3.2.1 Zero Crossing Detection Error

The phase of the Omega signal is measured by hard-limiting the signal and comparing signal zero crossing with reference clock zero crossing. The time difference between the two is converted to phase value.

Assuming a saturation ratio of 10:1, the transition from one limit to the other will take 12 degrees ($2 \times \sin^{-1} 0.1$ degrees) for a sinusoidal Omega signal). With 100:1 saturation, the transition is 1 degree. A 1-degree phase detection error corresponds with a position fix error of ± 0.02 nm (± 37.0 meters). (At an Omega frequency of 10.2 kHz, 16 nm corresponds with 360 degrees).

4.3.2.2 Phase Comparison Quantization Error

Omega receivers typically quantize phase in units of 1/100 of a wavelength (centilanes). Resolution accuracy at a frequency of 10.2 kHz is therefore 0.16 nm, or ± 0.08 nm (± 148.2 meters).

4.3.3 Receiver Clock Errors

As with Loran-C, there are two types of clock errors for Omega. The first is error associated with initial synchronization, and the second is a function of stability.

4.3.3.1 Clock Initialization Error

In the hyperbolic mode, clock initialization errors have minimal effect on position accuracy, because only the phase difference between incoming signals is measured, resulting in the cancellation of initialization errors.

Table 4-3. POSITION ERROR BUDGET SUMMARY FOR OMEGA

Error Source	Impact of Error (\pm nm) on Navigation System Use		
	Hyperbolic	Rho-Rho	Rho-Rho-Rho
Transmitter Timing Errors	0.08	0.08	0.08
Signal Detection Errors:			
Zero crossing detection	0.02	0.02	0.02
Phase comparison quantization	0.08	0.08	0.08
Receiver Clock Errors: [*]			
Initialization Drift	Negligible 2.5×10^{-4}	0.02 0.005**	0.02 2.5×10^{-4}
Signal Propagation Variations:			
Prediction	1.6	1.6	1.6
Random†	2.5	2.5	2.5
Position Fix Calculation Errors: [†]			
Earth model	0.2	0.2	0.2
Dead reckoning	0.025	0.025	0.025
Total System Position Error (RSS 2 drms):			
GDOP = 1	1.6	1.6	1.6
GDOP = 2	3.2	--	--

*Quartz clock unless otherwise noted.
**Rubidium clock or better.
†Excluded from RSS calculation.

In the rho-rho mode, initialization errors are significant because they add a constant error to the position fix. The clock is initialized by the use of either the four Omega navigation frequencies or differences between these frequencies. Frequency differences are used to resolve initial lane ambiguity. Nondifferenced frequencies subsequently are used for final correction of clock error.

If exact position and propagation characteristics are known at the time of initialization, and if the clock synchronization circuits provide comparable performance to the phase detection circuits, phase ambiguity of 1 degree can be expected in clock synchronization. This ambiguity corresponds with a position fix error of ± 0.02 nm (± 37.0 meters).

In the rho-rho-rho mode, a third Omega station is used to calculate clock offset. Theoretically, initial clock synchronization errors can be completely eliminated through repeated measurements of position. In reality, however, there is a residue of error dominated by the receiver's signal detection capabilities (± 0.02 nm).

4.3.3.2 Clock Drift Error

If the local oscillator is unstable and drifts in relation to the transmitter clocks, the system perceives this as a phase shift and computes an erroneous position. Table 4-4 summarizes the effect of clock drift on navigation accuracy for different types of clocks.

Table 4-4. ESTIMATE OF CLOCK STABILITY EFFECTS ON POSITION ERROR FOR OMEGA NAVIGATION

Clock Type	Short-Term Stability: One Part per:	Position Error (nm)		
		Hyperbolic (10-Second Update)	Rho-Rho (6-Hour Update)	Rho-Rho-Rho (10-Second Update)
Quartz	3×10^9	5×10^{-4}	1.8	5×10^{-4}
Rubidium	6×10^{11}	3×10^{-6}	1×10^{-2}	3×10^{-6}
Cesium	5×10^{12}	3×10^{-7}	1×10^{-3}	3×10^{-7}
Hydrogen Maser	1×10^{14}	2×10^{-8}	7×10^{-5}	2×10^{-8}

In the hyperbolic mode, the clock is phase-locked at least every 10 seconds (and more likely about once per second), so it needs to have only good short-term stability. In fact, the effect of drift is minimal if any high quality clock is used in the Omega receiver.

In the rho-rho mode, the clock is free-running during each leg of the flight and thus may not be resynchronized for two to six hours. Because of this extended operating period, clocks that are typically used are not stable enough to provide accurate rho-rho navigation over extended time periods.

In the rho-rho-rho mode, a third Omega station is used to estimate and compensate for the error resulting from clock drift. This readjustment occurs every 10 seconds, as in the hyperbolic mode. Therefore, the effect of drift will be minimal for any high quality clock used in the receiver.

4.3.4 Signal Propagation Variations

4.3.4.1 Prediction Error

Estimates of the error associated with inaccurate propagation modeling range from 20 centicycles (cec) to 50 cec, corresponding with a propagation distance of 3.2 to 8 nm at an Omega frequency of 10.2 kHz. For this analysis, 3.2 nm, specified as ± 1.6 nm, is assumed to be a typical propagation prediction error.

4.3.4.2 Random Error

Many influences on signal propagation cannot be predicted -- for example, sudden phase anomalies (SPAs), produced by sudden ionospheric disturbances (SIDs), and polar cap absorption (PCA), resulting from polar cap disturbances (PCDs). These anomalies can cause position errors of 2 to 8 nm -- an average error of 5 nm.

4.3.5 Position Fix Calculation Errors

4.3.5.1 Earth Model

As in Loran-C navigation, Omega navigation requires the use of a mathematical model of the earth. The possibility of a position fix error of ± 0.2 nm is used in this analysis.

4.3.5.2 Dead Reckoning

If an error rate of 5.5×10^{-3} nm per second is used (based on an along-track change of 20 knots), the 10-second dead reckoning period before the first update will result in a position fix error of 0.05 nm. Some Omega/VLF units use processing techniques that reduce the period of dead reckoning. By processing the VLF signals in parallel rather than in series with the Omega signals, a more continuous update capability can be achieved.

4.4 ERROR BUDGET FOR VOR/DME

Errors for VOR/DME are divided into the following categories:

- Bearing error components
 - Ground component radial error
 - Airborne component radial error
 - Course selection error
- Distance measurement errors
 - Ground component distance error
 - Airborne component distance error

- Area navigation computation error
- Total system error

Table 4-5 summarizes the impact of specific errors on navigation accuracy for the two classes of use in the VOR/DME system. Each error source is discussed in detail in the following sections.

Table 4-5. ERROR BUDGET SUMMARY FOR VOR/DME*		
Error Source	Impact of Error on Navigation System Use	
	Basic VOR/DME	RNAV VOR/DME
Bearing Errors:		
Ground component	$\pm 1.4^\circ$	$\pm 1.4^\circ$
Airborne component	$\pm 3.0^\circ (\pm 1.0^\circ**)$	$\pm 3.0^\circ (\pm 1.0^\circ**)$
Course selection	$\pm 2.0^\circ (\pm 0.5^\circ**)$	$\pm 2.0^\circ (\pm 0.5^\circ**)$
Distance Errors:		
Ground component	$\pm 0.1 \text{ nm}$	$\pm 0.1 \text{ nm}$
Airborne component	Between 0.1 nm and 1% of range	Between 0.1 nm and 1% of range
Area Navigation Computation Error	Not Applicable	$\pm 0.5 \text{ nm}$
Total System Error (RSS 20):		
Radial	$\pm 3.9^\circ (\pm 1.8^\circ**)$	$\pm 3.9^\circ \pm 0.5 \text{ nm}$ $(\pm 1.8^\circ \pm 0.5 \text{ nm}**)$
Distance	Between 0.5 nm (0.1 nm**) and 3% (1%**) of range	Between 0.5 nm (0.1 nm**) and 3% (1%**) of range

*All values reflect the proposed FAA standard for VOR, DME, and TACAN, unless otherwise noted.
**Obtainable.

4.4.1 Bearing Error Components

4.4.1.1 Ground Component Radial Error (E_{gr})

Radial signal error is the difference between the nominal magnetic bearing from the VOR transmitter to a point of measurement and the bearing

indicated by the signal at the same measurement point. Ground component radial error consists of (1) certain constant elements, such as course displacement errors and most site and terrain effect errors, which may be considered fixed for long periods of time, and (2) certain random variable errors that can be expected to vary about the essentially constant value. The ground component radial error is associated with the VOR transmitter and nominal signal path errors, but excludes other error factors.

Siting and propagation errors dominate VOR signal errors. Alignment of electronic radials with magnetic radials, and deviations of signal because of roughness, scalloping, multipath effects, signal bending, and refraction, are mostly uncontrollable factors that contribute significantly to siting errors. Signal propagation variations in the atmosphere have been demonstrated to contribute to a course error of 0.2 degree.

Extensive data collection by the FAA indicates an E_{gr} error value of ± 1.4 degrees (95 percent probability).

4.4.1.2 Airborne Component Radial Error (Ear)

Airborne component radial error is the error attributable to the inability of the airborne equipment to correctly translate the bearing information contained in the radial signal. This element embraces all factors in the airborne component that introduce errors in the information presented to the pilot. (Errors resulting from the use of compass information in some VOR and TACAN displays are not included.)

An Ear value of ± 3.0 degrees (95 percent probability) was used in defining the national aviation standard for the VORTAC system. The use of digital signal processing has reduced this error to a range between ± 0.75 and ± 2 degrees according to various equipment manufacturers. A value of ± 1 degree is specified in Table 4-5 as being obtainable.

4.4.1.3 Course Selection Error (CSE)

This error is the accuracy limitation of the omnibearing selector (OBS) units resulting from the resolution of the device and the inherent error of translating the pilot input to the avionic comparator. This comparator derives the difference between the actual computed radial and the selected radial required by the pilot. This difference is usually displayed on a course deviation indicator (CDI). Errors of the CDI are considered to be part of Ear.

A requirement of ± 2.0 degrees for CSE was established on the basis of accuracies achievable with analog dials. The advent of digital processing and displays permits pilots to set a desired course to within 1 degree.

4.4.2 Distance Measurement Errors

4.4.2.1 Ground Component Distance Error (E_{gd})

According to current requirements, ground component range accuracy must be maintained to within 0.1 nm.

4.4.2.2 Airborne Component Distance Error (E_{ad})

The airborne DME unit measures and displays the slant range distance between the aircraft and the ground station. The accuracy of this information must be maintained to within 3 percent of the actual distance, or ± 0.5 nm, whichever is greater. The digital revolution has markedly improved the accuracy of airborne DMEs beyond standard requirements. Manufacturers commonly quote airborne equipment accuracy of ± 0.1 nm to 1 percent of DME distance for general aviation equipment.

4.4.3 Area Navigation Computation Error (E_c)

When RNAV computation is used, an additional error contribution is specified and combined with the basic VOR/DME system error. The additional maximum RNAV equipment error allowed, per FAA AC 90-45A, is ± 0.5 nm.

Computation error includes error components contributed (1) by any input, output, or signal conversion equipment used, (2) by any computing element used, (3) by the display as it presents either aircraft position or guidance commands (e.g., course deviation or command heading), and (4) by any course definition entry devices used. For systems in which charts are incorporated as integral parts of the display, E_c necessarily includes charting errors to the extent that these errors actually result in errors in controlling the position of the aircraft in relation to a desired path over the ground. To be consistent, for symbolic displays not employing integral charts, any errors in waypoint definition directly attributable to errors in reference charts used in determining waypoint positions should be included as components of E_c . This type of error is difficult to quantify; in general practice, highly accurate published waypoint locations are used to the greatest extent possible to avoid charting errors (and to reduce workload).

4.4.4 Total System Error (E_s)

Assuming that the variable errors from various sources discussed are normally distributed and independent, the error components are combined in RSS fashion as follows:

$$\text{System radial error } (E_{sr}) = \sqrt{E_{gr}^2 + E_{ar}^2 + CSE^2 + FTE^2 + E_c^2}$$

$$\text{System distance error } (E_{sd}) = \sqrt{E_{gd}^2 + E_{ad}^2}$$

4.5 ERROR BUDGET FOR GPS

GPS errors are divided into the following categories:

- Satellite errors
- Signal propagation variations
- Receiver errors

These errors directly affect the range measurements from each visible satellite. User position is determined by the processing of independent range measurements.

Two levels of accuracy are associated with NAVSTAR GPS, corresponding with two different signal codes -- the precision code (P-code) and the less accurate coarse/acquisition (C/A) code. The range error budget for GPS, summarized in Table 4-6, reflects the errors associated with use of the C/A code only, since that is the only code to be made available for civil aviation applications. Position error is a function of the combined effects of the errors associated with each range measurement.

Table 4-6. RANGE ERROR BUDGET SUMMARY FOR UNRESTRICTED GPS (C/A CODE)

Error Source	Impact of Error (Meters) on Navigation System Use
Satellite Errors:	
Clock	1.0
Ephemeris	1.5
Orbital perturbation	1.5
Signal Propagation Variations:	
Atmospheric delay	3
Multipath	20
Receiver Errors:	
Measurement noise	10.5
Range quantization	2.66
Navigation algorithm	1.0
Total System Range Error (RSS):	
1σ	23.1 (0.01 nm)
2 drms	46.2 (0.025 nm)

Although the results shown in Table 4-6 are of interest, they are not necessarily indicative of the position fix accuracy that a civilian GPS user can expect when GPS becomes fully operational. The denial of accuracy that may be imposed by the Department of Defense will result in a degraded capability of determining position, possibly to a 2 drms accuracy of no better than 500 meters (0.27 nm).

The individual range error sources are discussed in the following sections.

4.5.1 Satellite Errors

4.5.1.1 Clock Error

The rubidium clocks currently used in the satellites are periodically updated by the ground control facility to maintain an accuracy better than 1 meter (1 σ).

4.5.1.2 Ephemeris Error

Each satellite transmits its position to a user receiver in the form of predicted ephemeris data. Errors in the ephemeris translate into position fix errors. Techniques for charting the ephemeris are believed to be accurate to within 1.5 meters (1 σ).

4.5.1.3 Orbital Perturbation Error

Influences such as variations in the earth's gravity gradient cause space vehicle perturbations. Such perturbations are projected to be 1.5 meters (1 σ).

4.5.2 Signal Propagation Variations

The GPS signal propagates from the satellite to the user through several mediums, including vacuum and an anisotropic atmosphere. Consequently, the propagation velocity varies as the signal passes through the ionosphere and troposphere and may experience multipath effects from reflection and refraction at various boundary layers and from objects near the receiver. The uncertainty associated with the modeling of these propagation characteristics contribute to the range error budget for GPS.

4.5.2.1 Atmospheric Delay Error

The time delay of the GPS signal passing through the ionosphere can be compensated for by one of two techniques. The first and most accurate means of calculating the delay involves comparing two frequencies of signal transmission, exploiting the fact that the overall delay is nearly inversely proportional to the square of the frequency. When dual-frequency measurements are not available, as is the case for the C/A signal, a second technique, modeling, provides the only means of compensation. The magnitude of the error depends on time of day, solar activity, geomagnetic latitude, and

other factors, which result in uncertainties of 1 to 30 meters. On the basis of projections of recent studies, an average value of 3 meters seems reasonable.

4.5.2.2 Multipath Error

The effects of multipath cannot be characterized through modeling, because the creation of multipath signals depends on the nature and location of reflective objects in relation to the receiver antenna. The magnitude of multipath errors has been estimated to be between 1.2 and 2.7 meters (1σ) for P-code operation. The degree of signal interference associated with multipath effects is inversely proportional to the code rate used. Since the code rate of the C/A signal is one-tenth that of the P-code, the multipath errors corresponding to the C/A code would be between 12 and 27 meters. For this study, an average magnitude of 20 meters is used.

4.5.3 Receiver Errors

In processing the received signal, the GPS receiver contributes to position fix error through suboptimal code lock-on caused by noise in the signal, internal accuracy limitations resulting from quantization effects, and inaccuracies inherent in the navigation solution.

4.5.3.1 Measurement Noise Error

The ability to accurately determine GPS range from a signal measurement depends on both the modulation of the selected code and the signal quality. In a signal environment characterized by a carrier-to-noise density ratio (C/N_0) of 30 dB-Hz, a code measurement error of 10.5 meters (1σ) has been projected for C/A code operation. This level of accuracy degrades rapidly as the C/N_0 worsens (approximately 22 meters at $C/N_0 = 25$ dB-Hz), imposing a requirement for external inputs when the C/N_0 falls below 20 dB-Hz. The addition of an external input, such as velocity, to the GPS position measurement process does not improve the accuracy of the GPS signals, but enhances the ability of the navigation algorithm to determine position.

4.5.3.2 Range Quantization Error

The user receiver generates replicas of the C/A codes and cross-correlates these locally generated signals with the signals received from the satellites. A tracking loop is used to establish synchronization between the two signals. The code tracking loop establishes maximum correlation between the received signal code and the internally generated reference code, defining the quantization of the receiver range measurement. Code tracking errors directly affect the signal phase measurements, which are resolved into a position fix. Current designs for code tracking loops provide a code resolution capability of 1 to 1.6 percent. Each bit in the C/A code is 978 nanoseconds long. At the speed of light, the duration of the code bit, or chip width, corresponds with 293.2 meters. A resolution

capability of 1.6 percent results in a range quantization of 4.6 meters. A quantization error of 2.66 meters (10) is specified when uniform distribution of the error is assumed over the range quantization value.

4.5.3.3 Navigation Algorithm Error

Implementation of a navigation algorithm contributes some error because of computer limitations, mathematical approximations, algorithm uncertainties, and timing delays inherent in the sequential nature of the computations. The magnitude of this error is estimated to be about 1 meter.

4.5.4 Operational Considerations

In addition to the errors associated with the various system components, two other factors that are not error sources in the conventional sense strongly influence the overall accuracy of GPS. These two factors, geometric dilution of precision (GDOP) and denial of accuracy, are included as operational considerations because they are not limitations in the same technical sense as the factors discussed in the previous sections.

4.5.4.1 GDOP

The concept of GDOP was initially developed in connection with Loran navigation, used in characterizing other radionavigation systems, and then extended to GPS. As applied to GPS, the value of GDOP is a composite measure that reflects the influence of satellite/user geometry on the accuracy of the navigation position fix.

The following parameters are contained in the GDOP composite:

- HDOP - Horizontal dilution of precision (two dimensions)
- VDOP - Vertical dilution of precision
- TDOP - Time dilution of precision
- PDOP - Position dilution of precision (three dimensions), or
$$\sqrt{(HDOP)^2 + (VDOP)^2}$$
- GDOP - $\sqrt{(PDOP)^2 + (TDOP)^2}$

Extensive analyses have been conducted to determine values of these GDOP parameters corresponding with various satellite geometries throughout the world. Unfortunately, most of the results published to date have been based on a constellation of 24 satellites rather than the configuration of 6 planes and 18 satellites currently proposed. The rms values* for the GDOP

*Derived from "Principle of Operation of NAVSTAR and System Characteristics," Reference 3.

parameters that were determined for the 24-satellite system can be thought of as minimum values for an 18-satellite system, as follows:

<u>GDOP Parameter</u>	<u>RMS Value</u>
PDOP	2.60
HDOP	1.45
TDOP	1.20
VDOP	2.20
GDOP	2.90

By multiplying the total 1 sigma range error (shown in Table 4-6) by the value of the GDOP parameter of interest, the magnitude of the position error can be determined. When values for PDOP or HDOP are applied to the range error, the result is a radial error ($\lambda\sigma$) in either three (PDOP) or two (HDOP) dimensions.

4.5.4.2 Denial of Accuracy

GPS is capable of providing extremely accurate globe positioning of about 50 meters (2 drms). The possible impact on national security in allowing unrestricted access to the accuracy of GPS has prompted extensive discussion of methods for denial of accuracy. The method that will most likely be used will deny the signal accuracy by altering the ephemeris and clock correction terms in the satellite navigation message to create range errors of an order of magnitude not yet agreed upon. It is believed, however, that the level of accuracy to be made available to nonmilitary users of GPS will be somewhat better than 500 meters (2 drms); the actual level will be based upon national security considerations.

4.6 SUMMARY OF TECHNICAL CAPABILITIES

Table 4-7 compares the technical capabilities of Loran-C, Omega/VLF, and GPS navigation systems with the requirements defined in FAA AC 90-45A. The nonprecision approach requirements specified in AC 90-45A are referenced to typical approach clearance zones. The FRP stipulates a nonprecision approach requirement of 100 meters, which is sufficient to allow a nonprecision approach capability at all airports. Since AC 90-45A is the currently acknowledged reference for certification of area navigation systems, it, rather than the FRP, will be used to provide the basis for comparing system capabilities.

Flight technical error (FTE) refers to the accuracy with which the pilot controls the aircraft as measured by his success in matching the indicated aircraft position with the indicated command or desired position on the display. (With autopilot coupling, FTE is more appropriately referred to as autopilot error.) FTE does not include blunder errors, which are gross errors in human judgment or attentiveness that cause the pilot to stray significantly from his desired path.

Table 4-1. SUMMARY OF TECHNICAL CAPABILITIES OF AREA NAVIGATION SYSTEMS

Type of Accuracy	Requirements*	Loran-C (±1m)			Omega/VLF (±1m)			IPS (±1m)			Nonprecision Approach		
		En Route	Terminal Route	Non-terminal Route	En Route	Terminal	Non-Precision Approach	50 m	300 m	500 m	50 m	300 m	500 m
Equipment:													
Cross-track	1.5°	1.12	3.33	1.25	1.25	1.53	1.6°	0.93	0.16	0.27	0.93	0.16	0.27
Along-track	1.5°	2.11	3.3	1.25	1.25	1.60	1.6°	0.93	0.16	0.27	0.93	0.16	0.27
Flight Technical:													
Cross-track	2.5°	1.5	3.5	2.00	1.00	0.50	2.00	2.00	1.00	1.00	1.00	0.50	0.50
Along-track	—	—	—	—	—	—	—	—	—	—	—	—	—
Total System:													
Cross-track	2.5°	1.50	3.60	2.02	1.02	0.56	2.00	1.68	2.00	1.02	1.01	1.04	0.52
Along-track	1.5°	1.10	3.36	3.25	3.25	1.60	1.60	0.93	0.16	0.27	0.93	0.16	0.27

*Source: AC 90-45A, Reference 23.

The VOR/DME navigation system is not shown in the comparison, because the requirements were based on the capability of the VOR/DME system. Thus, that system, by definition, satisfies the requirements. The three levels of GPS capability shown in the table correspond to two possible levels of accuracy denial -- 300 meters or 500 meters -- and a nondegraded accuracy of 50 meters. All entries in the table are 20 values.

As shown in the table, Loran-C systems are capable of satisfying en route, terminal, and approach accuracy requirements, assuming availability of a signal. Omega is unable to meet terminal and approach requirements and slightly exceeds the en route accuracy requirements. However, measured accuracy during flight has shown that Omega/VLF navigation systems are capable of an accuracy of ±1.5 nm. Even with signal accuracy degraded to ±500 meters, GPS can provide nonprecision approach capability, although this capability is marginal and does not take into consideration the impact on accuracy if less than four satellites are visible.

Table 4-8 presents the capabilities of the various navigation systems in terms of operational environments as well as flight phases. Suitability, as defined in the context of the table, reflects a possible rather than a certified capability to meet existing requirements. The capabilities of a particular system operating in a certain environment are judged on the basis of existing reference material. In addition, the suitability of a particular system to provide domestic navigation capability does not imply an ability to replace VOR/DME as the national navigation standard. Any navigation system considered as a replacement for VOR/DME must not only provide coverage and accuracy to the same level that currently exists, but also demonstrate some degree of improvement.

Although Table 4-7 indicates that Loran-C is sufficiently accurate to meet en route technical requirements, Loran-C chains do not provide oceanic coverage, as shown in Table 4-8. Also, there is currently no midwest Loran-C chain in the domestic United States, which limits signal availability. The suitability of Loran-C for terminal and nonprecision approach navigation is contingent upon signal availability. Omega/VLF provides worldwide coverage with an accuracy suitable for en route navigation but not sufficient for terminal or approach operations. GPS, even with a denial of accuracy to a level of 500 meters, would provide sufficient accuracy for en route, terminal, and some nonprecision approach navigation, given the continuous availability of four satellites. The limitation to the application of VOR/DME is the result of lack of coverage in oceanic, remote, and offshore areas.

Table 4-8. SUMMARY OF POSSIBLE APPLICATIONS FOR NAVIGATION SYSTEMS

Navigation System	Application Based on Accuracy and Coverage				
	En Route			Terminal	Nonprecision Approach
	Domestic	Oceanic	Remote Offshore		
Loran-C	Suitable*	No Coverage	Suitable	Suitable	Suitable**
Omega/VLF	Suitable	Suitable	Suitable**	Insufficient Accuracy	Insufficient Accuracy
GPS	Suitable	Suitable	Suitable	Suitable	Suitable**
VOR/DME	Suitable	No Coverage	No Coverage	Suitable	Suitable*

*When coverage is available.
**Under conditions when sufficient accuracy is attainable.

CHAPTER FIVE

OPERATIONAL EVALUATION OF NAVIGATION SYSTEMS

5.1 INTEROPERABILITY CONSIDERATIONS

Interoperability of navigation systems can be defined as the ability of individual systems to operate effectively in an environment where other dissimilar systems are operating concurrently. The degree of compatibility among systems provides a measure of their interoperability. The following factors influence compatibility:

- Coordinate systems
- Route structures
- Separation standards
- RF environment
- Equipment interface
- Flight procedures

Each of these are discussed in the following sections.

5.1.1 Coordinate Systems

All navigation systems measure aircraft position in relation to a particular coordinate system. Basic VOR/DME employs a polar coordinate reference system with the VORTAC as the origin. The resulting distance/bearing (ρ/θ) measurements define aircraft position in relation to the VORTAC. Knowledge of the geographical position coordinates of the VORTAC aids in determining the geographical position of the aircraft. Geographically oriented navigation systems such as Omega, Loran-C, and GPS are referenced directly to latitude and longitude.

Any process for determining position on the earth's surface involves an assumption of the shape of the earth. One of the following three basic approximations to the earth's shape can be used:

- Flat
- Spherical
- Ellipsoidal

Through this approximation, the coordinate system used in the airborne navigation processor is defined.

The coordinate system accurately defines the surface of the earth to provide the capability to navigate between points on the earth's surface. Unfortunately, the shape of the earth is irregular and cannot be easily described mathematically. The geometrical figure that most closely approximates the shape of the earth is an oblate spheroid, or ellipsoid of revolution, created by an ellipse rotating about its minor axis. The irregularity of the earth's surface, however, prevents any one ellipsoid from approximating more than a particular section of the surface. Because of this restriction, a number of reference ellipsoids have been defined, each providing a fit only to localized areas. The geodetic and geophysical parameters used to define a reference ellipsoid are referred to as a datum. The datum origin is generally the point at which the reference ellipsoid is tangent to the earth geoid (the surface of the earth coinciding with mean sea level).

Navigation errors can be introduced when the navigation process involves different datums. The earth model used by the airborne navigation computer is based on one particular datum, such as the North American Datum. Charted locations of navaids, landmarks, airports, and other land sites may or may not be defined with respect to that same datum. The magnitude of differences between datums is primarily a function of the distance between datum origins. In addition, the accuracy within a given datum decreases as one travels progressively farther from the datum origin. Thus the error associated with nonstandardization of a coordinate system is not a constant bias, but depends on the actual ellipsoids used and the location of the user with respect to the datum origins of the ellipsoids. As an example, differences between the coordinates defined in the Tokyo Datum and a center-of-mass-referenced datum defining the World Geodetic System (WGS-72) can be as great as 500 meters (0.27 nm).

As the accuracy of navigation systems continues to improve, the impact of factors such as charting inaccuracies becomes increasingly more significant. Table 5-1 presents the impact a charting error of 0.27 nm would have on the accuracy of a position fix determined by various navigation systems, in terms of the percentage of their respective system accuracy capability.

5.1.2 Route Structures

The high cost of fuel emphasizes the need to provide for flexible routing of aircraft to maximize fuel efficiency. Direct routing between origin and destination provides the shortest distance path, but wind conditions may suggest selection of a less direct path.

Although it would be desirable to allow aircraft equipped with RNAV equipment to fly direct routes from origin to destination without having to report intermediate VOR position fixes, such freedom can create conflicts. RNAV units generally compute great-circle flight paths. The great circle is constructed under the assumption that the earth is a perfect

Table 5-1. IMPACT OF CHARTING ERROR ON SYSTEM ACCURACY

Navigation System	System Accuracy	Percentage of Accuracy Degradation Due to Charting Error of 0.27 nm
Omega	2.5 nm	10.8
Loran-C	0.25 nm	108
RNAV VOR/DME	0.5 nm	54
GPS	300 m	167

sphere. Corrections are sometimes applied to account for the oblateness of the earth, but the spherical-earth assumption is frequently considered to be sufficiently accurate. However, for a flight between New York and Los Angeles, the differences between a spherical-earth assumption and use of the Clarke 1866 oblate spheroid model of the earth result in an east-west discrepancy of 6.5 nm and a north-south discrepancy of 0.5 nm.*

Not only do the differences among the position-fixing processes used in airborne navigation systems present potential conflicts, but certain ATC computer capabilities can also create complications. The ATC computer can project flight paths forward in time to aid prediction of possible collision conflicts. These extrapolations of current heading are either great-circle projections or rhumb-line projections. The shortest path between two points on a spherical earth is a great circle, which is created by the intersection of the earth's surface and a plane defined by the center of the earth and the points of origin and destination. A rhumb-line path connects origin and destination along a course that maintains constant true heading (i.e., the course crosses successive lines of longitude at a constant angle). The deviation between a great-circle path and a rhumb-line path connecting New York with Los Angeles is approximately 218 nm of lateral separation at the point of greatest divergence. This point occurs nearly midway between New York and Los Angeles. After this point, the paths begin to converge until they finally meet at the destination in Los Angeles. (It is interesting to note that there is a difference of only 1 percent in total distance traveled between the two paths.) Figure 5-1 is a graphical comparison of the two flight paths.

The magnitude of deviation between a rhumb-line path and a great-circle path is dependent on both direction and distance of travel. The shorter the distance, the less the deviation. Since the ATC computer provides flight-path projections for only short distances, possible errors are minimized, regardless of direction of flight.

*Equations used to obtain values specified throughout this chapter are given in Appendix B.

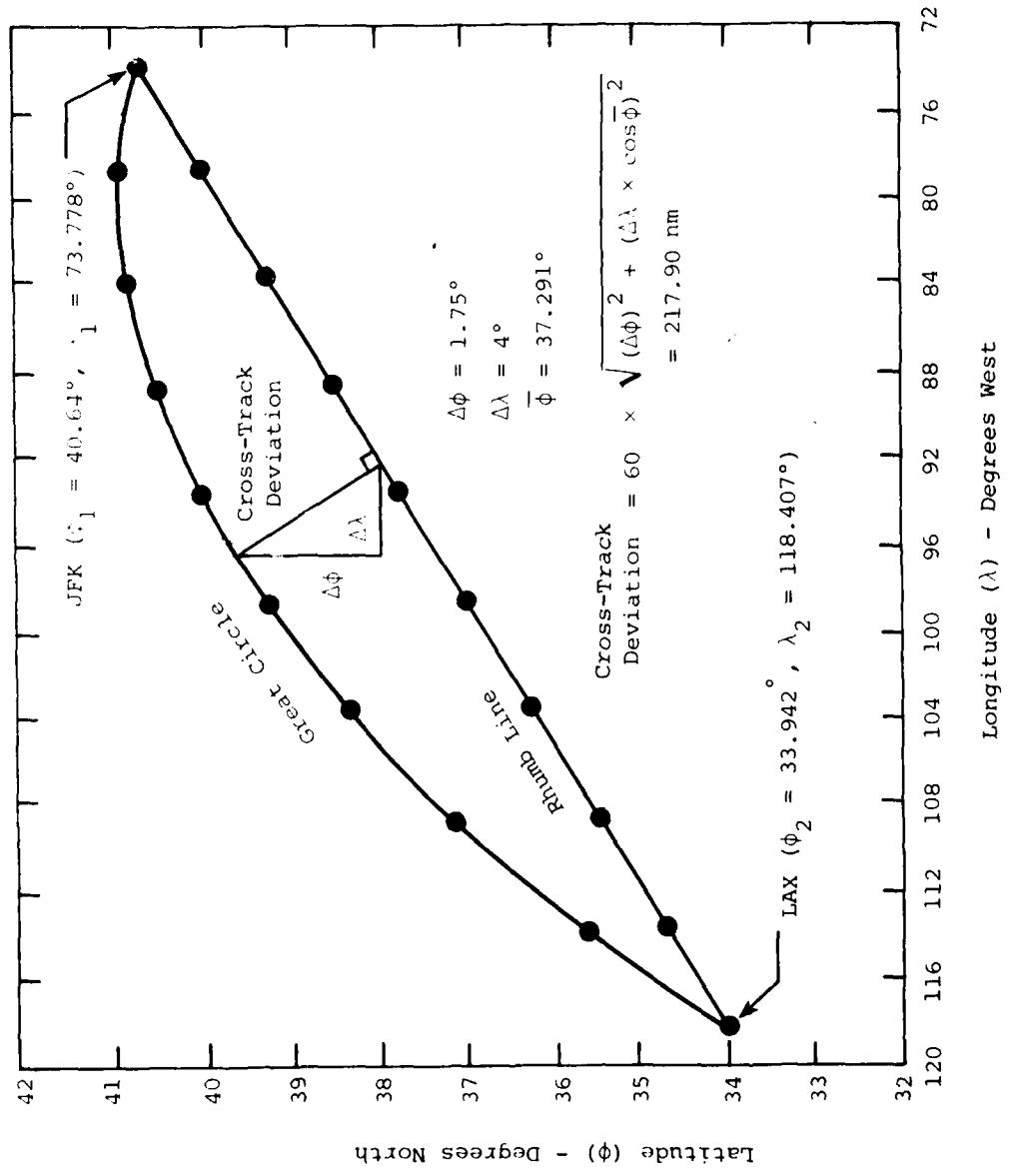


Figure 5-1. RHUMB-LINE ROUTE VERSUS GREAT CIRCLE ROUTE: NEW YORK (JFK) TO LOS ANGELES (LAX)

The following calculations illustrate the application of equations (given in Appendix B) to determine the flight path latitude (ϕ) at a given value of longitude (λ) for each path. The value of longitude used as an example is 93.778 degrees. ϕ_1 equals 40.64 degrees, λ_1 equals 73.778 degrees, ϕ_2 equals 33.942 degrees, and λ_2 equals 118.407 degrees.

Rhumb Line (RL):

$$\begin{aligned}\phi_{RL} &= \phi_1 + (\lambda - \lambda_1) \times \left(\frac{\phi_2 - \phi_1}{\lambda_2 - \lambda_1} \right) \\ &= 40.64 + (93.778^\circ - 73.778) \times \left(\frac{33.942 - 40.64}{118.407 - 73.778} \right) = 37.64^\circ\end{aligned}$$

Great Circle (GC):

$$\phi_{GC} = \tan^{-1} [(\tan Lv) \times \cos (\lambda - \lambda_1 - D\text{Lov})]$$

where

$$Lv = \cos^{-1} (\cos \phi_1 \sin C) = 40.79^\circ$$

$$C = \tan^{-1} \left[\frac{\sin (\lambda_2 - \lambda_1)}{(\cos \phi_1 \tan \phi_2) - (\sin \phi_1 \cos (\lambda_2 - \lambda_1))} \right] = 86.1564^\circ$$

$$D\text{Lov} = \sin^{-1} \left(\frac{\cos C}{\sin Lv} \right) = 5.8894^\circ$$

$$\text{Thus } \phi_{GC} = \tan^{-1} [0.8629 \times \cos (\lambda - 79.6674)] = 39.9247^\circ$$

If an aircraft is flying a great-circle route, and the ATC computer provides the controller with a rhumb-line projection of that flight, a serious conflict may develop. Such a possibility could be avoided if the ATC computer were emulating the same navigation techniques used by the aircraft. Unfortunately, standardization of a navigation technique does not exist. Radar surveillance is used to monitor deviations from intended routes, but the controller will not intervene unless a potential conflict is perceived.

5.1.3 Separation Standards

Separation standards have been developed historically on the basis of estimated system accuracies. The navigation system used as the reference standard in determining existing standards is VOR/DME. System accuracies are developed based on estimates of the individual accuracies of the navigation signal, the receiver, and flight technical error and provide a measure of the bounds of position error.

Position error is defined in terms of the technique used to determine position. GPS is a range system; VOR/DME is an angle and range system. Omega and Loran-C are hyperbolic navigation systems but can also be used in a ranging mode. The VOR contribution to VOR/DME position error is presented as an angle or a one-dimension distance at a defined range from the station. DME error is a percentage of the distance from the station. Position error in relation to Loran-C, Omega, and GPS is an elliptical area, the dimensions of which are determined by the geometry of the aircraft position in relation to the transmitters. The problem of compatibility of accuracy specifications when different systems are compared should be resolved by adoption of the 2 drms position error probability method.

5.1.4 RF Environment

Of the navigation systems studied -- VOR/DME, Loran-C, Omega, and GPS -- only DME involves transmission of an RF signal by the airborne unit. There are no indications that DME signals cause interference with reception of the navigation signals of VOR, Loran-C, or Omega. However, the airborne DME transponder may disrupt reception of GPS signals, depending on the proximity of the DME channel frequency to the frequency of the GPS signal.

Each navigation system is susceptible to certain types of external interference, but the question of compatibility concerns whether the existence of one navigation system adversely affects the use of another system. The only other known example of conflict is in the use of Loran-C when the user is in close proximity to the VLF transmitting stations used by Omega/VLF navigation systems. Test flights have indicated that reception of Loran-C signals is very poor when the user is within 15 nm of a VLF transmitter. The notch filters of airborne Loran-C units are unable to discriminate against the broad-band characteristics of the VLF signal.

5.1.5 Equipment Interface

The purpose of a navigation system is to provide a means of establishing and maintaining a route by which one can travel from point A to point B. In most applications, display of the deviation from the prescribed route is more useful for maintaining correct course than display of actual geographical position along the route. For this reason, the course deviation indicator (CDI) has become the primary means of control display between the navigation system and the pilot. All the navigation systems studied provide capability for interface to a CDI.

The navigation systems are not, however, interchangeable in terms of cockpit installation. Unique requirements associated with each system, such as antenna type, generally create the need for modifications to existing cockpit interface wiring when a change is made from one type of navigation system to another.

5.1.6 Flight Procedures

The question of compatibility with respect to flight procedures involves technique as well as capability. To adequately assess the operational performance of a particular navigation system, case studies were selected to represent operational environments in which the system must perform. The number of case studies necessary to emulate all possible scenarios is greater than the number that can provide an adequate measure of system interoperability. Interoperability is a measure of the ability of ATC to maintain safe separation of aircraft without giving special consideration to the types of navigation systems used. The methods by which ATC maintains lateral separation of aircraft are specified in the Air Traffic Control handbook as follows:*

- Clear aircraft on different airways or routes whose widths or protected airspace do not overlap
- Clear aircraft below 18,000 [feet] to proceed to and report over or hold at different geographical locations determined visually or by reference to NAVAIDS
- Clear aircraft to hold over different fixes whose holding pattern airspace areas do not overlap each other or other airspace to be protected
- Clear departing aircraft to fly specified headings which diverge by at least 45 degrees

Degrees of effectiveness of system interoperability can best be measured through scenarios that highlight the distinctions between system capabilities in different environments. Four scenarios were selected as being effective in demonstrating these differences, as well as being representative of each of the operational methods used by ATC to maintain lateral separation of aircraft. Additional scenarios were considered, but the resulting values of operational merit for respective systems duplicated those determined in a previously defined scenario. Duplication of results, regardless of differences in scenarios, was avoided so that the possibility of bias would be minimized. The scenarios were applied to a mix of navigation systems operating concurrently in common domestic en route airspace.

Each system is reviewed in terms of response to the following controller requests:

1. "Turn left heading zero two five."
2. "Cleared to fly direct Fargo."
3. "Track outbound on the Green Bay VOR zero nine zero radial."
4. "Report crossing Jones intersection."

**Air Traffic Control, Reference 31.*

Parameters of concern include the following:

- Means of establishing course or track
- Means of maintaining course or track
- Consequence of loss of signal
- Pilot workload
- Controller workload

The four case studies are evaluated in Section 5.2.

5.2 CASE STUDIES

The following case studies are intended to provide insight into the operational effectiveness of the navigation systems studied by exercising those systems in realistic situations. Differences in the functional characteristics of airborne control/display units (CDUs), such as push-buttons versus knobs for data entry, must not be considered relevant when the effectiveness of types of navigation systems is compared. The computational, rather than the mechanical, effectiveness associated with use of a particular navigation system is of interest. Although the functional design of a CDU can affect pilot workload, it is not the intent of this study to determine the optimal design of a CDU. Rather, this study must establish the inherent limitations of a navigation system without regard to packaging considerations that could theoretically be accommodated by any system. The limitations identified through application of the case studies are summarized in Section 5.3.

5.2.1 Case Study One

5.2.1.1 Description

Circumstance

The first case study considers pilot compliance to an ATC request to "turn left heading zero two five." The aircraft is assumed to be flying at a true airspeed of 350 knots at 17,500 feet en route due east over the continental United States. Choice of aircraft airspeed and altitude is completely arbitrary and does not reflect any intentional discrimination relating to class of aircraft. The aircraft is being vectored under instrument flight rules (IFR) conditions to avoid a thunderstorm and is being monitored by radar. Wind is out of the northwest at 30 knots.

Applicable Systems

In this scenario, single VOR and non-RNAV VOR/DME systems are considered separately. RNAV navigation systems -- VOR/DME, Loran-C, Omega, and GPS -- are not evaluated independently, since the response is common to all.

5.2.1.2 Application of Scenario

General Comments

The request calls for a left turn to establish a magnetic heading of 25 degrees. Since all aircraft are equipped with a magnetic compass, a request to fly a specified heading vector is accommodated without reliance on anything more sophisticated.

Single VOR

A VOR receiver indicates the magnetic bearing of the VOR transmitter with respect to the aircraft antenna. This information is not sufficient to establish a heading reference. Therefore, a magnetic compass is still required to establish heading, even when the aircraft is equipped with a VOR receiver.

Non-RNAV VOR/DME

An airborne VOR/DME system provides distance as well as bearing to a VORTAC. Addition of the distance information makes possible a relative position fix with respect to the VORTAC from which the signals emanate. Although a VOR/DME system does not provide heading information, successive manual plotting of relative position fixes provide an indication of ground track. Knowledge of ground track, however, does not indicate heading. Consequently, a magnetic compass is used to verify heading.

RNAV

All RNAV units, regardless of type, demonstrate the same degree of operational capability in responding to a request for a heading change. For this reason, the following description applies equally to RNAV VOR/DME, Loran-C, Omega/VLF, and GPS.

Area navigation systems establish a ground-track reference, rather than a heading reference, by which the desired flight path is maintained. To establish a flight path, origin and destination must be entered into the RNAV unit. A ground track is then computed by the airborne computer, and deviations from that track are measured through processing of the navigation signals received.

Destination entered into the RNAV unit can be defined in a variety of formats, one of which is bearing and distance from some location already known to the RNAV unit. If the RNAV unit has been successfully navigating before the request for a heading change, current position is a known location. In most RNAV units, current position is defined as Waypoint 0. Another waypoint, which can then be entered into the unit, is at a bearing of 025 degrees from Waypoint 0. The distance entered can be nearly anything, since the object is to establish a direction of track, not a specific destination. However, for practical reasons relating to computational overflow and underflow, the distance used should be reasonable -- 100 nm, for example. Directing the RNAV unit to initiate a direct-to computation

from current position to a waypoint defined as 025 degrees bearing, 100 nm distance from current position establishes a ground-track angle of 025 degrees as the desired track.

A track of 025 degrees does not necessarily correspond to the heading of 025 degrees flown by aircraft using a magnetic compass in accordance with the ATC request. The difference between track and heading is wind. Flying a heading of 025 degrees at a true airspeed of 350 knots in the presence of a 30-knot northwest wind results in a track of 029.6 degrees with a ground speed of 341 knots, as illustrated in Figure 5-2. Therefore, to comply with a request to fly a heading of 025 degrees in this scenario, the pilot would have to input a track of 029.6 degrees when establishing his "to" waypoint. However, when a pilot is instructed to fly a heading, he is expected to fly a magnetic heading without regard to ground track.

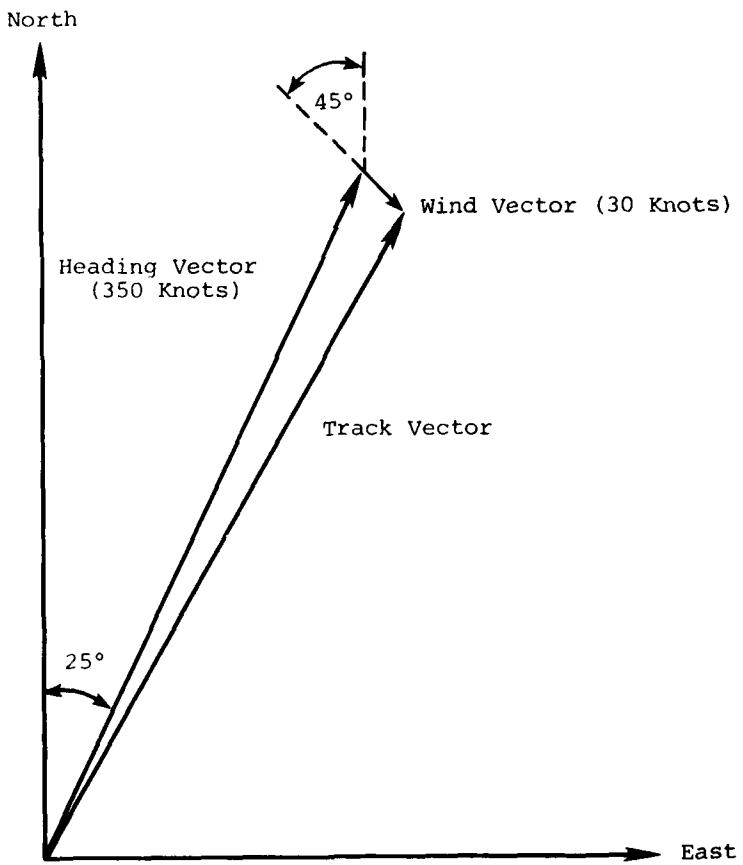


Figure 5-2. RELATIONSHIP BETWEEN HEADING AND TRACK VECTORS

Calculation of the required track of 029.6 degrees requires knowledge of wind speed, wind direction, and true air speed, and application of the law of cosines. An alternative to this computation is to input the desired heading as the track angle and compensate for the wind by monitoring heading and modifying the track input accordingly. Although this alternative does not require manual calculations, it is no less demanding in terms of pilot workload because of the requirement to perform numerous operations with the RNAV unit over an extended time period.

As is evident from the foregoing description, a certain degree of difficulty is associated with using an area navigation system to fly a requested heading. Although heading may be a display parameter associated with area navigation systems, it is generally not a computational by-product of the area navigation process, but rather is the output of an external sensor. The source of heading information is a magnetic compass. It is therefore common practice for pilots to revert to the magnetic compass when responding to such requests. In aircraft equipped with area navigation systems, the magnetic compass is generally associated with a magnetic heading reference system stabilized by a gyro, referred to as a gyrocompass. The horizontal situation indicator (HSI) is a magnetic heading reference system that allows either heading selection via the magnetic compass or course selection when coupled with an area navigation system. An HSI can also be operated in a VOR-only mode, in which case course selection represents a desired VOR radial. In the area navigation mode, desired course is computed, rather than selected, and displayed on the HSI as a function of the current waypoint-to-waypoint track leg.

5.2.1.3 Discussion of Results

Relative Comparisons

None of the navigation systems evaluated are suited for efficient response to a request for a heading change, because their primary function is to compute and display track, not heading.

System Mix Conflicts

A conflict could arise if two or more aircraft were requested to fly heading vectors and each pilot programmed the heading into the respective hold modes associated with the navigation systems used. The navigation systems are referenced to ground track, while ATC requests are referenced to heading through the magnetic compass. Depending on winds and direction of flight, an aircraft holding track might not respond satisfactorily in accordance with the controller's intentions. A burden would then be placed on the controller, who would find it necessary to issue new vectors to compensate for the inconsistencies. (A pilot flying track when instructed to fly heading would be in violation of ATC regulations.)

5.2.2 Case Study Two

5.2.2.1 Description

Circumstance

This case study considers pilot response to an ATC clearance to "fly direct Fargo." At the time of clearance the aircraft is near Green Bay, Wisconsin, 390 miles east of the Fargo, North Dakota, VORTAC. The aircraft is operating in visual meteorological conditions in daylight. The pilot first filed a flight plan originating at Chicago, flying direct to Fargo. Because of traffic considerations, the aircraft was vectored to Green Bay; upon arrival, direct clearance to Fargo was issued.

Applicable Systems

All systems are considered independently in this scenario -- single VOR, Non-RNAV VOR/DME, RNAV VOR/DME, Loran-C, Omega/VLF, and GPS.

5.2.2.2 Application of Scenario

Single VOR

In this situation, the aircraft is initially out of range of the Fargo VOR signal, regardless of altitude. Therefore, a direct-to clearance cannot be accommodated and would not be issued, when a single VOR receiver is used and the "to" destination is beyond reception range.

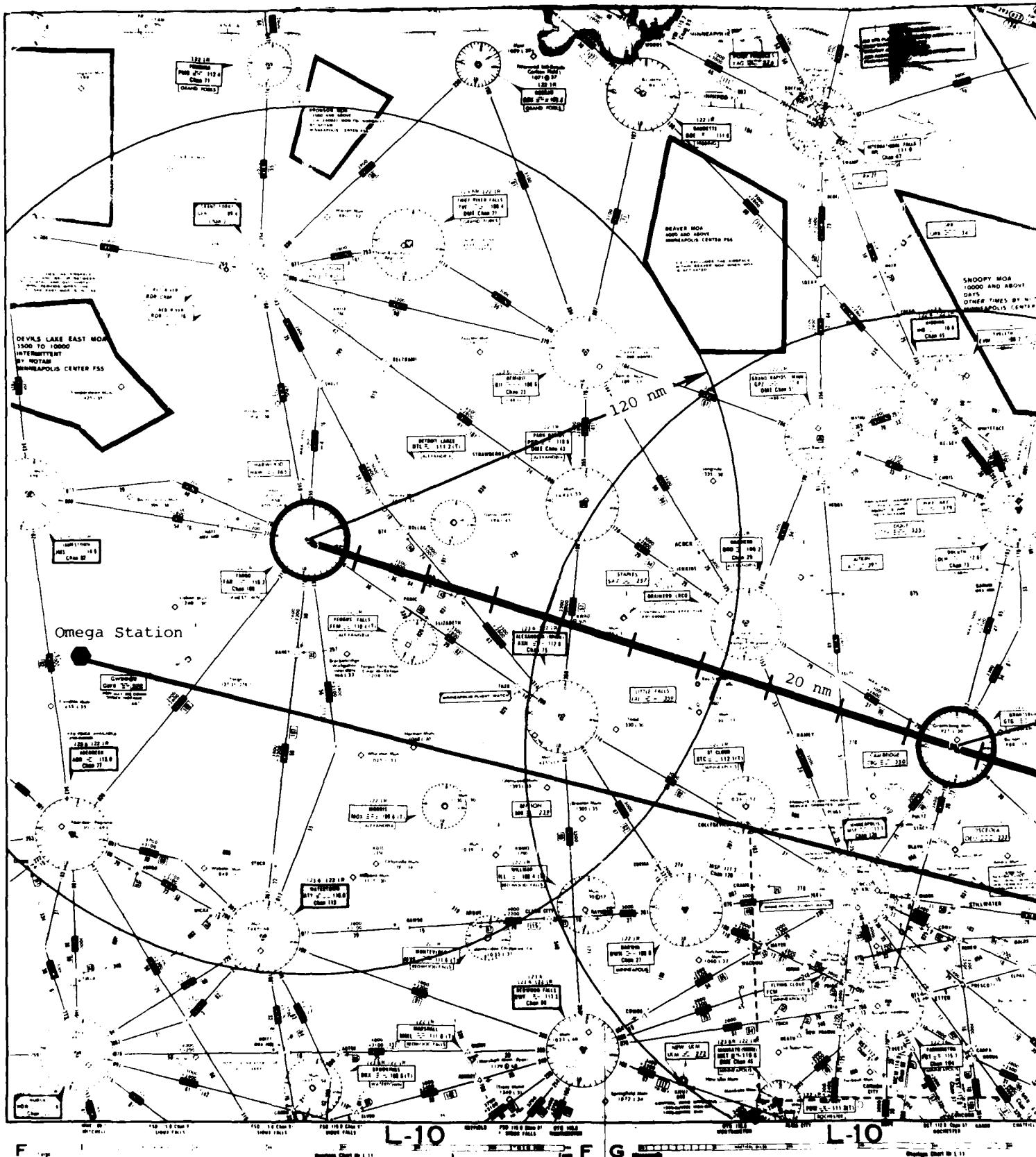
Non-RNAV VOR/DME

Addition of a DME receiver is of no consequence in this scenario. Because the VORTAC defining the destination is beyond range of the VOR/DME unit, any possibility of a direct-to capability is eliminated.

RNAV Single VOR/DME

When a VOR/DME-based area navigation system is used, position offsets can be applied to appropriate VORTACs along the flight path to establish intermediate waypoints between origin and destination. The waypoints should be spaced along the flight path at distances that ensure overlapping of VORTAC signal coverage, thus accommodating direct routing between any two points. If a circular coverage area with a radius of 120 nm is assumed for each VORTAC, three VORTACs are necessary to provide continuous coverage between Green Bay and Fargo, as illustrated in Figure 5-3.

For the RNAV VOR/DME unit, all waypoints are entered in terms of bearing and distance from a particular navaid, which is defined by a frequency input. Waypoints other than origin and destination are typically defined as points on the flight path that are directly abeam of the reference navaids. (An abeam point is defined as the intersection of the flight path and a line perpendicular to the flight path drawn to the navaid.) As the aircraft progresses along the flight path, the various waypoints defined in the stored flight plan list are sequentially activated.



Source: Enroute Low Altitude - U.S. Flight Information Publication, Reference 27.

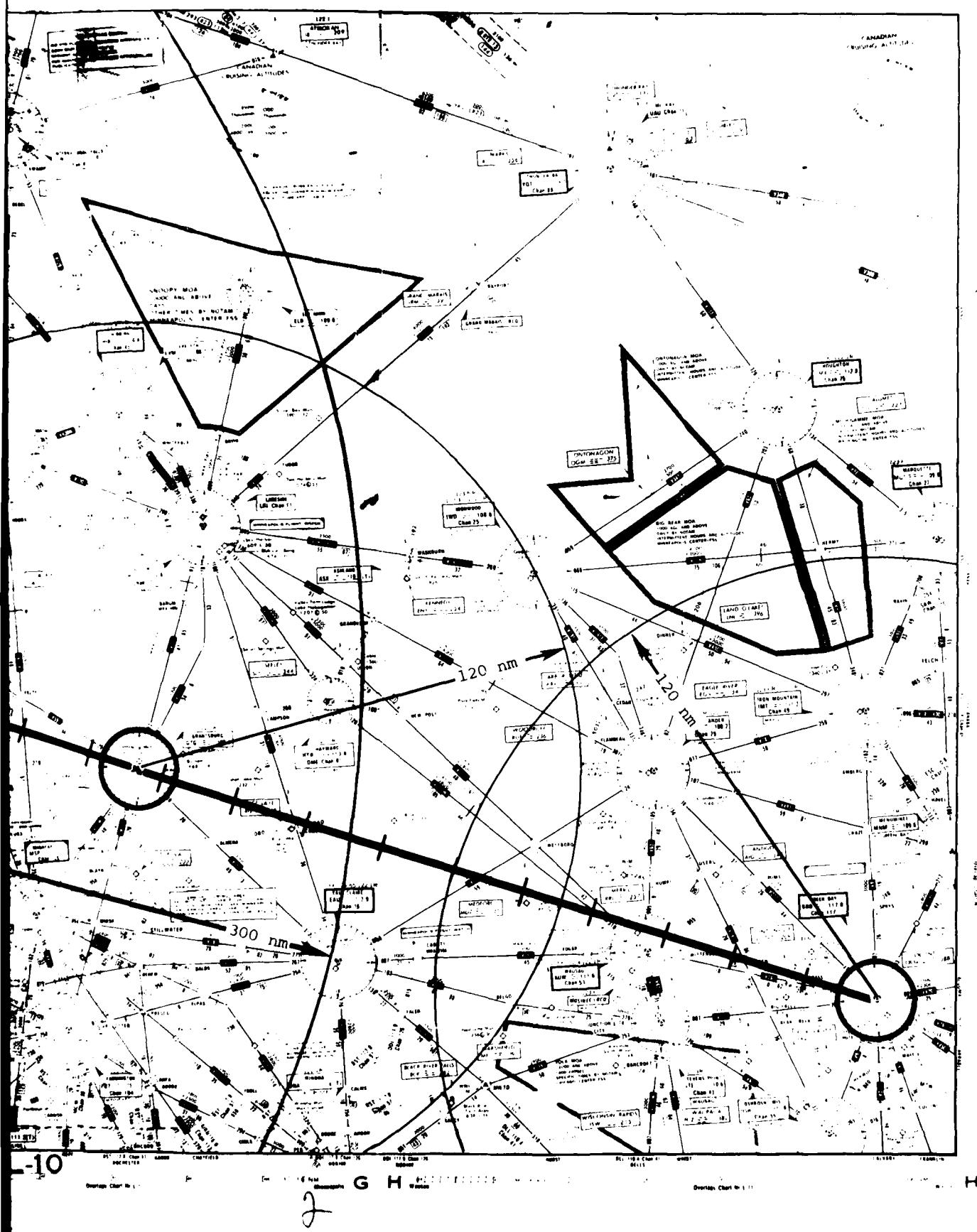


Figure 5-3. FLIGHT PATH BETWEEN GREEN BAY, WISCONSIN, AND FARGO, NORTH DAKOTA

As stated in the description of this scenario, the original flight plan was for a direct route between Chicago and Fargo. Appropriate navaids were manually selected from aeronautical charts to serve as waypoint references. Either manual calculations or a ground-based computer was then used to compute the magnetic bearing and distance of the navaid abeam points on the flight path. The diversion to Green Bay, which could not have been predicted, results in the necessity of manually charting a new great-circle course and defining new waypoints. If the pilot has access to an RNAV en route chart for the area, an established RNAV route such as J976R can be used as defined. The reference navaids and corresponding waypoint coordinates are already defined and need only to be entered into the RNAV unit. If such a chart is not available, however, or if none of the established RNAV routes are acceptable, the pilot must expend a significant amount of effort to establish a new flight plan. This situation will now be considered.

The first task for the pilot is to draw a line connecting origin and destination on his aeronautical flight planning chart. A straight line on a Lambert conformal chart, the chart typically used, defines a great-circle path with a constantly changing heading. If the only chart available is a Mercator projection, a straight line will define a rhumb-line path, with constant true heading.

Once the path has been defined, the pilot must select navaids along the route that will provide adequate overlapping coverage. A line can then be drawn between the navaid and the flight path, intersecting the flight path at a right angle. The point of intersection defines the waypoint. The magnetic bearing and distance from the navaid to the waypoint can then be approximated from the chart. On the flight path between Green Bay and Fargo, as indicated in Figure 5-3, at least two waypoints must be entered into the RNAV unit in addition to the destination (which was already defined), so that adequate coverage is provided.

If, as the flight progresses, a navaid used to define a waypoint is not transmitting because of a sudden unannounced shutdown, a new navaid must be selected for use as soon as possible. Although this situation does not necessarily require charting a new course, it does require calculating new waypoint coordinates and entering them into the RNAV unit.

RNAV Multiple VOR/DME

The navaid data base typically included in RNAV multiple VOR/DME systems allows selection of any navaid and access to its identifying parameters (such as coordinates, frequency, elevation, and magnetic variation) through input of a three-letter navaid identifier (ident). The destination of Fargo, North Dakota, is entered simply as FAR. A waypoint list is used to enable definition of distinct flight legs. However, a direct-to clearance requires the input of only origin and destination. Waypoint 0 in the waypoint list is generally a reserved location that maintains current position. When a direct-to clearance is initiated, current position is designated the origin, and destination corresponds to the waypoint defining Fargo.

Selection of primary and secondary navaids to ensure continuous signal coverage throughout the flight is automatic. Station-selection algorithms first identify candidate navaids in terms of proximity to the flight path. Final selection of primary and secondary navaids is based on geometrical considerations for obtaining the greatest accuracy. Loss of a navaid while en route would pose no problem, since the station-selection algorithm would automatically search for and acquire a replacement.

Loran-C

Loran-C is, by definition, an area navigation system. The only inputs required are origin and destination. As with RNAV VOR/DME units, a waypoint list is used to define intermediate flight legs. Current position is always maintained and made available through a reserved location in the waypoint list. Under the assumption that a navaid data base does not exist, the destination (Fargo) must be entered in terms of latitude, longitude, and magnetic variation specified on the aeronautical chart for the Fargo VORTAC.

The flight from Green Bay to Fargo was selected in consideration of Omega and Loran-C coverage areas. The flight path passes through an area representing worst-case United States domestic coverage for Omega and Loran-C navigation. A midwest Loran-C chain, currently in the planning stages, would dramatically improve Loran-C coverage in the United States. The origin, Green Bay, Wisconsin, is well within the coverage area of the Loran-C Great Lakes chain. Fargo, North Dakota, however, is beyond the published coverage area of the Great Lakes chain and is also out of range of the Loran-C chain for the west coast of the United States. The published limits of Loran-C coverage are approximations based on a signal-to-noise ratio of 1:3 and a fix accuracy of 0.25 nm (95 percent 2 drms). Therefore, as the pilot progresses toward Fargo from Green Bay, degradation in signal strength could cause loss of navigation integrity when the aircraft is 310 nm out of Green Bay, with 80 nm still remaining to Fargo.

Omega/VLF

Unlike Loran-C, Omega/VLF is considered a worldwide navigation system. As with Loran-C, however, the only inputs required for establishment of a direct-to-great-circle route are specifications of origin and destination. Several Omega sets provide access to a data base, allowing input of waypoints in terms of alpha designators.

For this scenario, then, the pilot inputs "FAR" as the "to" waypoint and selects current position as the "from" waypoint. A great-circle route between Green Bay and Fargo is thereby established, and Omega and VLF stations within reception range are used to monitor progress along the flight path.

Seven Omega transmitters are currently operational. They are located in Norway, Argentina, La Reunion, North Dakota, Hawaii, Liberia, and Japan. Of these, Norway, La Reunion, and Argentina cannot provide coverage over the route described in this scenario. (The Australian transmitter, when

declared operational, would provide coverage over this flight path only at night.) During the time of flight (daytime), Green Bay is within the coverage area of North Dakota, Hawaii, and Liberia. Liberia and Hawaii provide coverage throughout the flight (assuming they are not shut down for scheduled maintenance). The flight enters the outer fringe of the coverage area of the Japan transmitter only upon arrival at Fargo.

Published Omega coverage areas are based on a signal-to-noise ratio of 1:10. Omega units generally deselect use of a station that is within 300 nm of the receiver to avoid near-field effects. Although some units deselect stations within 600 nm, 300 nm is considered to be more typical. The North Dakota Omega station is only 76 nm southwest of Fargo. Therefore, the North Dakota station will be deselected when the aircraft is approximately 166 nm out of Green Bay, as illustrated in Figure 5-3.

Coverage along the flight path is provided by stations as follows:

<u>Distance to Destination</u>	<u>Available Omega Stations</u>
400 nm	North Dakota; Hawaii; Liberia
300 nm	Hawaii; Liberia
200 nm	Hawaii; Liberia
100 nm	Hawaii; Liberia
0 nm	Hawaii; Liberia; Japan

Satisfactory hyperbolic or rho-rho-rho navigation is possible when three Omega stations are being received. When only two Omega stations are available, hyperbolic navigation is not possible. Rho-rho navigation is possible with only two stations, but the accumulation of error associated with not having an independent measurement for determining user clock bias prevents extended use of this mode. These considerations make navigation using only Omega stations impossible along this flight path when the published coverage charts are used as the basis for judgment.

However, use of VLF signals to augment Omega navigation provides capability not otherwise possible. Signals from several VLF transmitting stations can be received along the flight path between Green Bay and Fargo. Therefore, an Omega/VLF navigation system can provide satisfactory navigation in this case study. Addition of a VLF signal-processing capability to the Omega unit has no effect on the user in terms of pilot interface to the unit.

GPS

GPS, a satellite-based navigation system, is by definition an area navigation system. The capabilities planned for a low-cost GPS navigation system are essentially similar to those previously described for the Loran-C receiver. It is assumed that a VOR/DME data base is not used. Origin and destination are entered in terms of latitude and longitude. A waypoint list is used to define intermediate flight legs, if needed, and current

position is available in a reserved location in the waypoint list. The route between Green Bay and Fargo is established by entering the latitude and longitude of Fargo into the waypoint list and defining that waypoint as the "to" waypoint; current position serves as the origin and is defined as the "from" waypoint. As has been assumed previously, the navigation unit in use has been operational for some time, and the received signals provide satisfactory navigation capability at the time the direct-to clearance is issued.

With an 18-satellite configuration of three satellites in six orbital planes, more than four satellites are not always in view over the continental United States above an elevation angle of 10 degrees. Four satellites are required for three-dimensional navigation by GPS; as long as four satellites remain in view, navigation by GPS between Green Bay and Fargo can be easily accomplished. After establishing origin and destination, all the pilot needs to do with the navigation system for the duration of the flight is to monitor and correct deviation from the flight path as indicated by the navigation system display. However, in a situation where less than four satellites are in view, the navigational capability of GPS would be reduced dramatically. Even with an altimeter providing a vertical position measurement to the GPS receiver, only three satellites in view would result in degraded position accuracy for instances where satellite geometry, in conjunction with the altimeter measurement, creates a symmetrical arrangement resulting in poor HDOP. Without the altimeter input, user clock bias could not be estimated with only three satellites -- again resulting in degraded position accuracy.

5.2.2.3 Discussion of Results

Relative Comparisons

Comparison of the units considered in this case study led to the following conclusions:

- Non-RNAV systems provide direct-to capability only when the intended destination is a VORTAC and the airborne receiver is within range of the transmitted signal.
- For RNAV VOR/DME-based navigation systems, automatic station selection eliminates the need for the pilot to concern himself with station acquisition and signal monitoring. Such capability makes the RNAV VOR/DME unit comparable to existing Loran-C and Omega/VLF units in terms of functional use. If a standard man/machine interface is incorporated into the design of all navigation system units, pilots could ideally operate any navigation system unit without regard to the type of signals processed.
- Manual station selection of navaids, although less desirable than automatic station selection, can be made acceptable in VOR/DME navigation systems through the use of a navaid data base. Specification of a navaid by either its three-letter ident or its frequency eliminates the need for time-consuming and error-prone entry of latitude, longitude, frequency, and magnetic variation of each desired navaid.

- Current designated airways are defined on aeronautical navigation charts in terms of VORs, justifying the use of existing airway descriptors in the design of non-VOR/DME-based systems. Such design philosophy includes the use of a VOR/DME data base, as well as versatility in input/output formats to include bearing and distance information.

System Mix Conflicts

This case study concerns an aircraft using the on-board navigation system to establish and maintain a direct course to a final destination. Assume that two aircraft, each with a different navigation system, are given clearance to the same destination from the same position fix. One aircraft is using an Omega navigation system, while the other aircraft is equipped with a VOR/DME RNAV system that has rhumb-line navigation capability. Obviously, both aircraft could not depart from the same fix at the same time. If the controller has spaced the aircraft to ensure adequate longitudinal separation, the controller could expect the aircraft to follow the same flight path, since they are traveling between the same origin and destination. However, differences in course-calculation techniques (rhumb line versus great circle), in the accuracy with which intermediate waypoints are defined (manual charting versus computer calculation), in the accuracies of systems (2.5 nm for Omega versus 0.5 nm for VOR/DME), and in the coordinate systems used (spherical versus Clarke 1866) all interact to cause varying degrees of deviation between flight paths. Again, the burden is on the controller to monitor the magnitude of the deviations and decide on appropriate corrective action when necessary. Table 5-2 associates distance disparities with each of these conflicts for a flight of 392 nm between Green Bay, Wisconsin, and Fargo, North Dakota. (The discrepancy in path creation associated with manual charting versus computer calculation is not easily quantified and is therefore not included in the table.) The equations used to obtain the distance differences associated with path selection and earth model are shown in Appendix B.

Table 5-2. ACCURACY CONFLICTS IN CASE STUDY TWO

Element of Conflict	Cause of Conflict	Resultant Distance Disparity (nm)
Path Selection	Rhumb line versus great circle	7.11
Navigation System	Omega versus VOR/DME	3.00
Earth Model	Spherical versus Clarke 1866	1.30

Figure 5-4 illustrates the way the navigation distance disparities shown in Table 5-2 can combine to result in a distance difference of 10.2 nm. Therefore, although each aircraft has been cleared to the same destination from the same origin, the route width required to contain all flight paths is greater than the current standard route width of 8 nm for domestic en route flights when within 51 nm of a VOR.

Case study two was for a flight of 392 nm. For longer flights, the contribution to relative position displacements resulting from differences in path selection and earth models increases. As an example, for a flight from New York to Los Angeles, the maximum cross-track distance between a rhumb-line path and a great-circle path is 218 nm.

5.2.3 Case Study Three

5.2.3.1 Description

Circumstance

This case study considers an ATC request to "track outbound on the Green Bay VOR zero nine zero radial."

Applicable Systems

The single VOR system is discussed independently; Non-RNAV VOR/DME systems, both single and multiple, are discussed jointly, as are both single and multiple RNAV VOR/DME systems. Also discussed, as common systems, are Loran-C, Omega, and GPS.

5.2.3.2 Application of Scenario

Single VOR

In this scenario, the single VOR performs satisfactorily. The VOR receiver is tuned to the frequency of the Green Bay VOR. The pilot then establishes his position in terms of bearing to the VOR. Depending on the magnitude of difference between present course and desired course along the 090-degree radial, the pilot determines an appropriate course-cut angle by which the 090-degree radial can be intercepted without too much overshoot. Once track on the 090-degree radial is established, the pilot will continue to monitor the VOR bearing indicator to maintain a reading of 090 degrees until the controller provides further instructions. The only difficulty that could be encountered would be fading of the VOR signal, if the request to maintain track is not altered before the aircraft is out of range of the VOR.

Non-RNAV VOR/DME

Existence of the DME does not significantly affect the capability of the system to satisfy the ATC request. The aircraft is still flown so that a VOR bearing indication of 090 degrees is maintained. The DME readout is helpful only in monitoring distance from the VOR so that ATC can

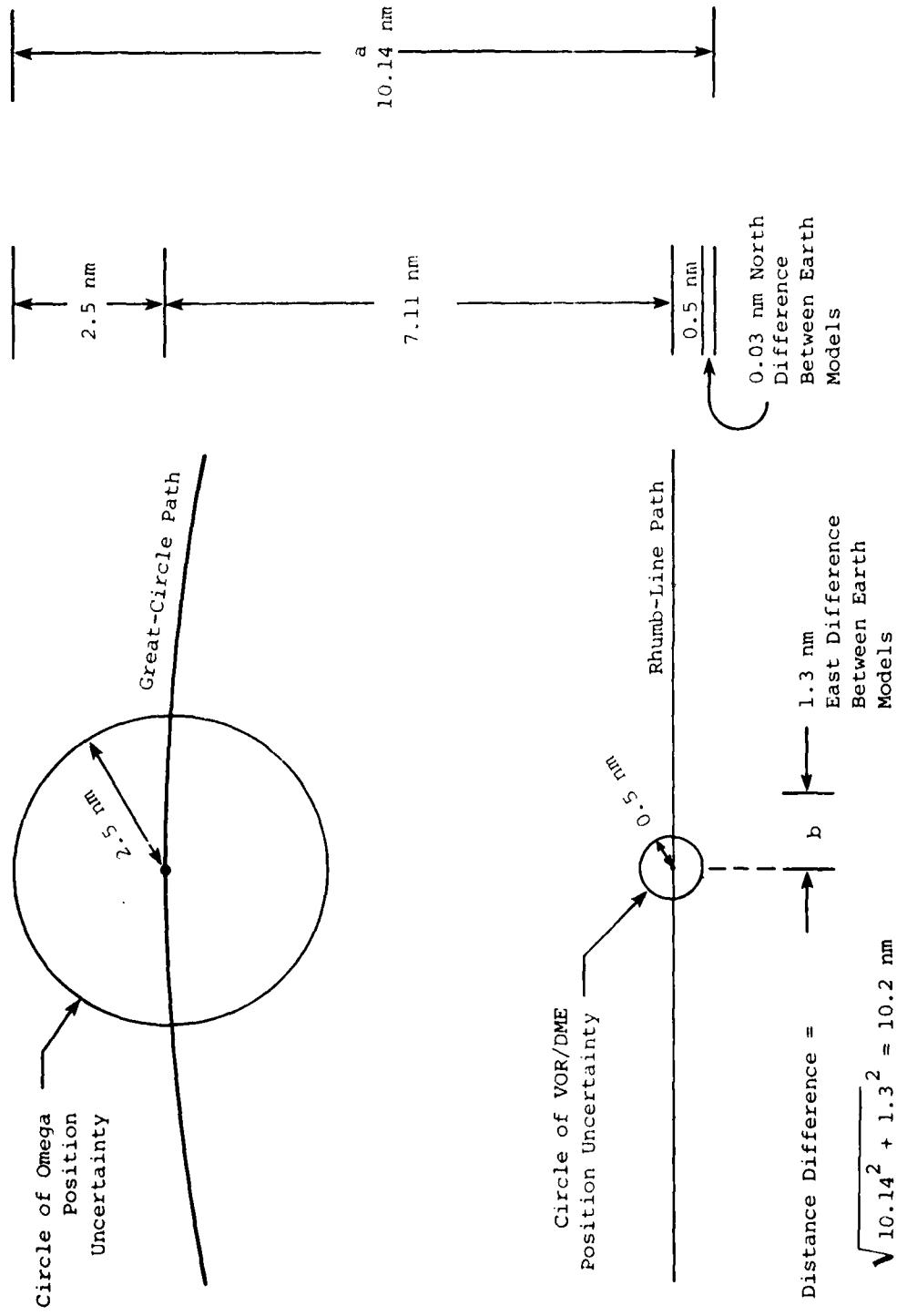


Figure 5-4. PICTORIAL REPRESENTATION OF SYSTEM MIX RELATIONSHIPS FOR CASE STUDY TWO

be notified (before complete loss of signal) if this distance becomes too great.

RNAV VOR/DME

The workload necessary to establish an RNAV route to comply with this request can be avoided by recognition that the full capability of the navigation system is not needed in this situation. Rather, the response should be as described for the non-RNAV VOR/DME navigation system.

Loran-C; Omega; GPS

For navigation systems not referenced to VOR signals, a flight path coincident with the Green Bay VOR radial of 090 degrees must be defined. This can be achieved by first defining the origin of the RNAV flight path to be the latitude and longitude of the Green Bay VOR, as read from the aeronautical chart. Destination can then be entered as a bearing/distance offset from the origin; the bearing would be 090 degrees, and the distance could be, say, 100 nm. Once this flight leg is activated, a course deviation would be indicated. Response to the deviation would establish track along the 090-degree radial. An advantage of these RNAV systems is that they are not susceptible to loss of the VOR signal, and therefore loss of reference, as the aircraft becomes increasingly distant from the VOR along the radial.

5.2.3.3 Discussion of Results

Relative Comparisons

By requiring the aircraft simply to maintain a constant relative bearing to a VOR, this case study illustrates the most basic use of VOR-based navigation systems and the premise on which airways were established. Therefore, VOR-based navigation systems surpass other navigation systems in the ease with which compliance to the request is achieved. That does not mean, however, that Loran-C, Omega, or GPS navigation systems would have difficulty defining a VOR radial; such a procedure is, in fact, quite easy. The point is that, in terms of a relative comparison, a VOR navigation system can perform more naturally in this environment than any other system.

System Mix Conflicts

The VOR station, which provides the signal used by the VOR-based navigation system, is at a fixed location on the earth. VOR receivers can navigate in relation to the VOR without regard to the actual geographical coordinates of the VOR as long as their destination or flight path is also defined with respect to the VOR.

Non-VOR based navigation systems must use geographical coordinates to represent a VOR used for position reference. Conflicts could occur if the geographical coordinates used by Loran-C, Omega, or GPS navigation systems do not correspond to the actual location of the VOR. This could result from error in pilot input for navigation systems with no access to a data

base or from the airborne processor's use of an earth model substantially different from the model defining the reference chart.

The possibility that various types of navigation systems may not agree upon the absolute position of a reference VOR could create conflict. The seriousness of this situation is a function of the degree of difference in perceived location of the VOR. Error in pilot input presents the greatest potential for conflict. A mistake of only one arc minute in latitude would cause a displacement of 1 nm between the basis of reference and the actual VOR. Availability of a data base would eliminate the potential for such errors (if the data base were error-free).

In this case study, as in all situations, the controller is responsible for monitoring compliance to requests. If an aircraft does not satisfactorily respond to a directed request, the controller must take corrective action. It would be confusing if a pilot with a non-VOR-based navigation system had established a track on a ninety-degree bearing from a waypoint corresponding with the coordinates of the Green Bay VOR and was then told by ATC that he was flying a track parallel to the requested track, but with an offset of 10 nm. The pilot would subsequently lose confidence in his navigation system, revert to magnetic heading, and request vectors, thus increasing the burden on the controller.

5.2.4 Case Study Four

5.2.4.1 Description

Circumstance

The last case study to be considered is an ATC request to "report crossing Jones intersection." The "Jones intersection" denotes one particular frequently used position fix that is defined in terms of two bearings from two VORs. The request is similar to "report crossing the Green Bay three one zero radial two five mile fix," which is referenced to a single VORTAC.

Applicable Systems

Single VOR, non-RNAV single VOR/DME, and RNAV single VOR/DME are discussed independently; multiple VOR/DME, both non-RNAV and RNAV, are discussed jointly. Also discussed as common systems are Loran-C, Omega, and GPS.

5.2.4.2 Application of Scenario

General Comments

An intersection is a defined waypoint in the National Airspace System (NAS). Intersections are referenced to VORs in terms of bearings, and/or bearing and distance, and are specified as such on aeronautical charts.

Single VOR

The VOR receiver can be tuned to one of the reference VORs and can provide navigation along the VOR radial on which the intersection is located. The pilot establishes track on the course radial, compensates for any drift resulting from wind, and estimates time of arrival at the intersection through knowledge of airspeed. Just before the estimated time of arrival at the intersection, the pilot tunes the VOR receiver to the off-course station and monitors radial crossings. Time of passage occurs when the desired intersecting radial is crossed.

Non-RNAV Single VOR/DME

Addition of DME to the VOR receiver allows navigation to any point referenced to a single VOR, in terms of both bearing and distance. Two techniques are used to establish point of passage over the defined waypoint when a non-RNAV VOR/DME navigation system is used. One method is to establish track on the reference VOR radial on which the intersection is defined. The DME readout is then monitored for indication of convergence to the distance specification for the intersection. Coincidence of measured bearing and distance with desired bearing and distance signifies passage over the intersection and can be so reported to ATC. A second method is used when a circular arc is flown about the reference VOR, and a DME range is held corresponding to the specified distance of the intersection from the reference VOR. Monitoring of VOR bearing readout then indicates convergence on the intersection and subsequent passage.

Both of these techniques are routinely used; the choice corresponds with the flight path for which ATC clearance was granted. ATC does not require a report of passage over an intersection if the flight plan is not along one of the VOR radials defining the intersection.

RNAV Single VOR/DME

Each RNAV waypoint in a single VOR/DME navigation system is defined with respect to a particular VORTAC. The Jones intersection can be designated a waypoint because it is intended to be on the flight path; it can therefore be defined in accordance with the charted bearing and distance from the reference VORTAC. Distance to this waypoint can then be directly monitored via the navigation system display. However, the need to establish a new waypoint imposes on the pilot the additional workload of inputting the frequency of the reference VORTAC and the bearing and distance from that VORTAC, which define the waypoint. Since the addition of a new waypoint in the RNAV unit does not have to overwrite existing waypoints, the pilot can easily revert to the previously designated waypoint once the aircraft has passed over the intersection.

Multiple VOR/DME

A multiple VOR/DME navigation system is well-suited to meet the requirements imposed in this case study regardless of whether or not the system has RNAV capabilities. One of the VOR/DME receivers of the non-

RNAV system can be dedicated to the VORTAC providing the reference for the intersection, while the other receiver can be available for primary navigation. For an RNAV multiple VOR/DME system, the unit can be used in the manner described for an RNAV single VOR/DME system.

Loran-C; Omega; GPS

All remaining RNAV systems (Loran-C, Omega, and GPS) provide the capability to define waypoints in terms of latitude and longitude coordinates. Therefore, the coordinates of the Jones intersection can be entered into the RNAV system to define a waypoint, and subsequent distance to the intersection can be directly monitored.

An obstacle to the ease with which RNAV systems can comply with the ATC request in this case study is the infrequency with which position fixes on charts are specified in terms of latitude and longitude in addition to bearing and distance. As an alternative to entering the latitude and longitude of the intersection, the coordinates of the VOR from which the Jones intersection is referenced can be entered to define a waypoint reference. A bearing and distance offset from this reference can then be entered to define the Jones intersection, the actual desired waypoint.

5.2.4.3 Discussion of Results

Relative Comparisons

VOR/DME systems are better suited for response to this case study request than are non-VOR/DME-based navigation systems for the reasons stated in the discussion of Case Study Three (Section 5.2.3.3).

System Mix Conflicts

Because this case study presents the same potential for conflict as did the last case study, the discussion for Case Study Three also applies to this situation.

5.3 SUMMARY OF CASE STUDIES

Table 5-3 summarizes the four case studies as they relate to six performance ranking criteria. Although the rankings are intended to indicate the relative operational capability of each case study, totaling the numbers in each column leads to some interesting observations. The level of capability for each system can be ranked according to the value of the sum of the codes; the lower the value, the more capable the system. This method of ranking system capability assumes that all case studies are of equal significance in their relationship to performance. In addition, it must be remembered that although VOR/DME, Omega, and Loran-C are ranked in accordance with currently existing levels of performance and coverage, GPS is evaluated with respect to a projected level of performance capability.

Table 6-6. RANKING OF NAVIGATION SYSTEM PERFORMANCE IN CASE STUDIES

Case Study	Ranking*							
	Non-RNAV			RNAV				
	Single VOR	Single VOR/DME	Multiple VOR/DME	Single VOR/DME	Multiple VOR/DME	Loran-C	Omega/VLF	GPS
1 (Fly Destination)	*	6	6	6	6	6	6	6
2 (Fly Direct To)	6	5	5	3	2	5	1	1
3 (Fly Radial)	1	1	1	1	1	2	2	2
4 (Report Position)	4	1	1	1	1	2	2	2
Total	16	13	13	11	10	15	11	11

*The ranking criteria for this table are as follows:

- 1 - Requires primarily pilot monitoring.
- 2 - Requires some manual calculations and/or routine interaction between pilot and unit.
- 3 - Requires periodic equipment or periodic manual corrections by pilot.
- 4 - Requires a significant amount of manual calculations and/or a high level of pilot interaction with unit.
- 5 - An objective cannot be met due to lack of signal coverage.
- 6 - An objective cannot be met due to limitations of system capability.

A single VOR system is shown in the scenarios to be the least operationally capable system. The RNAV multiple VOR/DME system is the most effective system, since the current ATC environment is predicated on the VOR/DME system. Until ATC capabilities are modified to allow non-VOR/DME-based navigation systems to take full advantage of their operational capabilities, use of such systems will be subjected to constraints that diminish their effectiveness. The RNAV single VOR/DME system, although obviously less capable than the other RNAV systems, is as functionally effective overall as Omega/VLF and GPS, in the context of the given scenarios. (Level of system accuracy was not a consideration in determination of operational effectiveness.) Loran-C was given a lower ranking than Omega/VLF and GPS only because of lack of Loran-C coverage in the area of interest defined in Case Study Two. If adequate Loran-C coverage within the United States were available, Loran-C would be ranked equally with Omega/VLF and GPS.

As a result of the case study evaluations, the navigation systems may be listed in descending order of effectiveness as follows:

- RNAV multiple VOR/DME
- RNAV single VOR/DME, Omega/VLF, and GPS
- Single VOR/DME

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

Currently available navigation systems offer numerous combinations of capabilities. The multitude of choices results from the different requirements imposed by different users, mandated by particular applications. The most basic decision to be made by a user is the selection of the particular type of navigation system (Loran-C, Omega/VLF, VOR/DME, or GPS) that best suits his needs. The most critical criteria considered in this initial selection process include signal accuracy and coverage. Table 6-1 summarizes each navigation system's ability to provide sufficient coverage and accuracy to be considered acceptable in different operational environments and flight phases. VOR/DME, Omega, and Loran-C were evaluated in terms of currently existing levels of performance and coverage, while GPS was evaluated with respect to a projected level of performance capability.

Table 6-1. SUMMARY OF POSSIBLE APPLICATIONS FOR NAVIGATION SYSTEMS

Navigation System	Application Based on Accuracy and Coverage				
	En Route			Terminal	Nonprecision Approach
	Domestic	Oceanic	Remote Offshore		
Loran-C	Suitable*	No Coverage	Suitable	Suitable	Suitable**
Omega/VLF	Suitable	Suitable	Suitable**	Insufficient Accuracy	Insufficient Accuracy
GPS	Suitable	Suitable	Suitable	Suitable	Suitable**
VOR/DME	Suitable	No Coverage	No Coverage	Suitable	Suitable*

*When coverage is available.
**Under conditions when sufficient accuracy is attainable.

Loran-C has sufficient accuracy to meet all en route requirements, but the limited number and coverage area of Loran-C station chains restrict its current use to only a subset of en route applications. Use of Loran-C for terminal and nonprecision approach navigation, if approved, will be limited to areas where signals are available.

Omega/VLF provides worldwide coverage, with an accuracy suitable for en route navigation but not sufficient for terminal or nonprecision approach operations.

GPS, even with a denial of accuracy to a level of 500 meters, would provide sufficient accuracy for en route, terminal, and many nonprecision approach navigation operations, assuming continuous availability of four satellites.

Because VOR/DME navigation is the basis upon which domestic navigation standards were developed, it therefore provides an acceptable level of accuracy. Lack of coverage in oceanic, remote, and offshore areas resulting from line-of-sight limitations and unavailability of suitable sites limit the application of VOR/DME.

On the basis of the results of the case studies of operational performance capability, the navigation systems may be ranked in descending order of overall effectiveness as follows:

- RNAV VOR/DME
- GPS
- Omega/VLF
- Loran-C

The operational effectiveness of each navigation system was measured by comparing the systems in terms of the ease with which they could be used to meet the stated objective of the particular case study. Emphasis was placed on the limitations associated with the navigation system, not on the functional capabilities of particular CDU designs.

Selection of RNAV VOR/DME systems as the most operationally effective is to be expected, since the current ATC environment is predicated on VOR/DME. Loran-C was given a lower ranking than Omega/VLF and GPS only because of limitations in current Loran-C coverage, which affected navigation performance during a particular case study.

The case studies identified an impact on pilot and controller workload when a geographically referenced navigation system was utilized in a station-oriented, procedural environment. Pilot workload was primarily affected by the differences between non-RNAV and RNAV navigation systems and the operation of those systems in situations not optimally suited to their specific capabilities.

The results of the case studies also revealed some potentially serious inadequacies regarding the characterization of performance of individual navigation systems. Accuracy of navigation systems has improved to the point where some systems are capable of a greater degree of accuracy than the reference against which accuracy is measured. Differences between earth models, which provide the basis for determining geographical position, can be greater than the accuracy capability of some navigation systems. Differences between possible flight paths (great circle versus rhumb line) when area navigation systems are used can far exceed specified route widths, even though the two paths have the same origin and destination. At the point of maximum deviation, there is a cross-track difference of 218 nm between the great-circle path and rhumb-line path between New York and Los Angeles. Differences in sky wave propagation models used in Omega navigation systems can result in differences in accuracy ranging from 3.2 nm to 8 nm.

Unrestricted use of area navigation techniques could result in such diversity of routing that controllers would be overburdened in their attempts to maintain separation of aircraft without conflict. Two forms of action can be taken to promote safe and efficient use of the capabilities of area navigation systems:

- Adoption of standards that define accuracy reference parameters
- Modernization of the ATC system so that ATC can accommodate the capabilities of area navigation systems

Table 6-1 indicates which navigation systems are capable of providing service in each application area, reflecting a probable rather than certified capability to meet existing requirements. Navigation systems and possible combinations of systems that can provide navigation capability in all operational environments and flight phases represented in Table 6-1 are as follows:

- GPS
- GPS and VOR/DME
- GPS and Loran-C
- GPS and Omega/VLF
- VOR/DME and Omega/VLF
- VOR/DME, Omega/VLF, and Loran-C

This list seems to suggest that GPS is the leading contender for selection as the standard navigation system. Such selection could accommodate all existing requirements. However, to support the adoption of GPS as the primary navigation system of the future would be premature at this time. Acceptance of GPS depends on the resolution of the technical, operational, economic, and institutional issues relevant to its benefit to the civil aviation community. The absence of GPS in the role of a primary navigation system requires the selection of a suitable navigation system mix to be based on currently existing systems.

Of the navigation systems studied that are currently operational, only two combinations provide full navigation capability in terms of minimum requirements for all operational environments in all flight phases -- (1) VOR/DME and Omega/VLF; and (2) VOR/DME, Omega/VLF, and Loran-C.

Although it would seem that the combination of VOR/DME with Omega/VLF would be the most appropriate in terms of minimizing the number of systems required, Omega/VLF does not currently provide the accuracy desired for offshore navigation. Loran-C provides not only increased accuracy for offshore navigation, but also terminal navigation capability in remote areas where VOR/DME is not suitable. Omega is not accurate enough for terminal navigation. Therefore, by the process of elimination, only one combination of navigation systems is able to meet the technical and operational requirements in the context of existing conditions -- VOR/DME, Omega/VLF, and Loran-C.

APPENDIX A

DETAILED SYSTEM DESCRIPTIONS

1. LORAN-C

1.1 History of Development

Loran-C (Long-Range Navigation) was developed in 1957 to provide higher accuracy and longer-range capability than Loran-A. The United States Coast Guard assumed responsibility for operation of the system in August 1958. In 1974, Loran-C was selected as the United States government-provided navigational system for civil marine use in United States coastal areas.

1.2 Facilities

All Loran-C transmitters operate at a fixed frequency of 100 kHz and must confine 99 percent of their radiated energy within the band of 90 to 110 kHz. The 100 kHz carrier frequency provides a near optimum signal-to-atmospheric-noise ratio for a range of 1,000 to 2,000 kilometers (621 to 1,242 nautical miles). Loran-C signals are transmitted with a peak power of four megawatts via a single vertical antenna tower, which may be as high as 1,350 feet. The ground plane required for transmission of Loran-C ground waves consists of an extensive network of wires buried in the ground to a radius of about 1,000 feet. All Loran-C transmitting stations are equipped with cesium frequency standards, which allow each station to maintain synchronization to absolute time without the need of reference to another station.

Loran-C transmitting stations form chains, each of which consists of a master and two to four secondary (slave) transmitting stations separated from the master by 600 to 800 miles. The geometry of the various chains is shown in Figure A-1. Figure A-2 shows the coverage provided by Loran-C, with the exception of the Canadian East Coast and Commando Lion chains. (The Commando Lion chain has stations located in Korea and Japan. Although it is used by the United States Air Force, it is not officially available to civilian users. The Canadian East Coast chain uses existing stations from other chains -- two from the Northeast United States chain and one from the North Atlantic chain.)

Current proposals are to expand Loran-C coverage in Spain, France, Norway, Canada, Russia, Hawaii, and mid-continent United States. It is doubtful that Loran-C will ever be made available in the Southern Hemisphere.

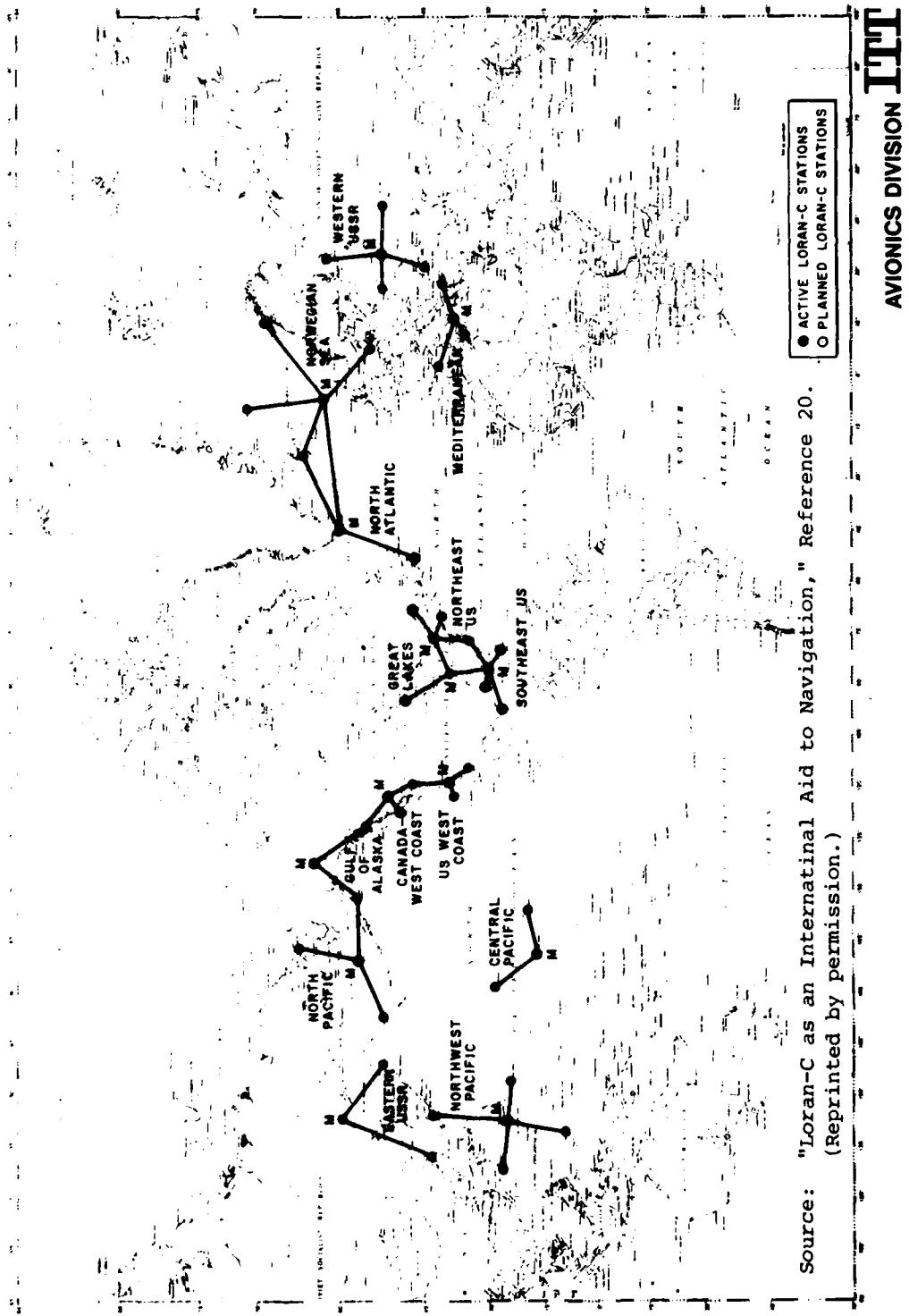


Figure A-1. LOCATIONS OF EXISTING AND PLANNED LORAN-C TRANSMITTING STATIONS THROUGHOUT THE WORLD

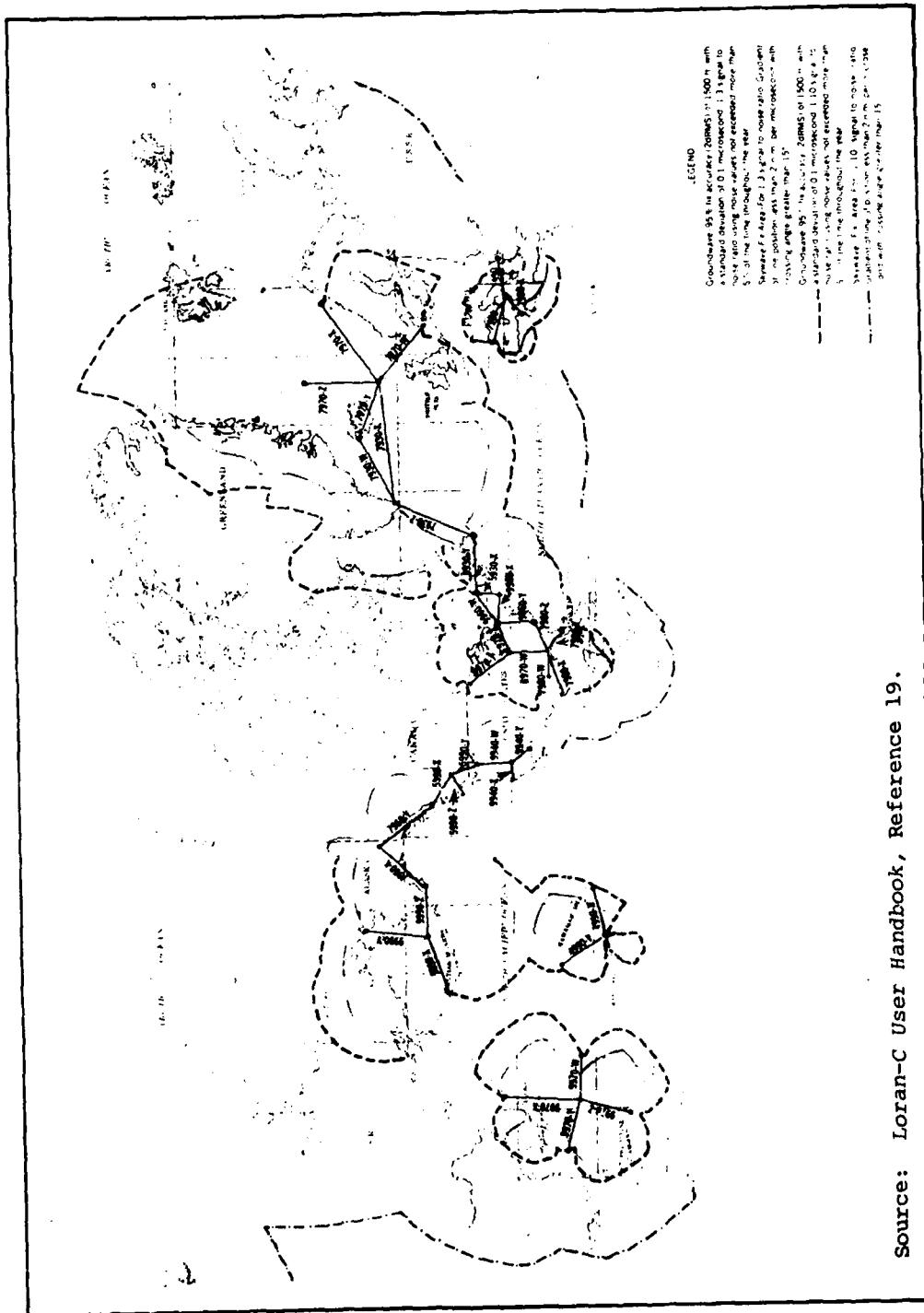


Figure A-2. COVERAGE DIAGRAM FOR LORAN-C

Loran-C navigation is based on time difference (TD) measurements between the user and the transmitters of the appropriate chain. Each chain is monitored by use of one or more system area monitor (SAM) stations within the coverage area to observe the TDs of each master-secondary pair. If an observed TD varies from the calibrated control TD by half of the prescribed control tolerance (± 200 nanoseconds or better), the SAM directs a change in the timing of the secondary station to remove the error. If the observed TD differs from the control TD by more than the control tolerance, the transmitted signal is coded to advise users that the TD is unusable. For convenience, letters are used to designate the stations in a chain. The master station is referred to as M, and the secondary stations are denoted as W, X, Y, and Z.

1.3 Signal Characteristics

The transmitting stations of a Loran-C chain transmit groups of pulses at a specified group repetition interval (GRI). The master station transmits its pulses in groups of nine at a repetition rate of 10 to 25 groups per second. The transmissions of the secondary stations are delayed, with respect to the time of arrival of the signal from the master, by a specified time called the secondary coding delay. This delay ensures that signals from two or more stations in a chain cannot overlap in time anywhere in the coverage area. The GRI must be of sufficient length to allow time for transmissions of the master (10,000 microseconds [μs]) and each secondary station ($8,000 \mu s$ per station) and for the secondary coding delays. The minimum GRI is therefore a direct function of the number of stations and the distance between them. The particular GRI specified for each chain is selected so that adjacent chains do not cause mutual interference.

Each station transmits one pulse group per GRI. The master pulse group consists of eight pulses spaced $1,000 \mu s$ apart. A ninth pulse, transmitted $2,000 \mu s$ after the eighth, is used for identification of the master. To warn of an error in the transmissions of a particular station, the ninth pulse is turned on and off in a specified code denoted as blink. Pulse groups for secondary stations contain eight pulses spaced $1,000 \mu s$ apart and use the first two pulses for blink. All secondaries use the same code, which is automatically recognized by most modern Loran-C receivers.

Each pulse within a group is designed to build up and decay slowly, defining the envelope shape shown in Figure A-3. The zero crossing point near $30 \mu s$ of the start of the pulse is identified as the third-cycle zero crossing. Confining transmission sampling to only the first three cycles eliminates interference from minimum time-delay sky waves. Tracking of a cycle zero crossing other than the third results in a bias error, the sign and magnitude of which are determined by the direction and number of cycle shifts. This form of error is categorized as cycle-to-envelope discrepancy (CED), commonly referred to as cycle-jump error. When it occurs, the error is typically a single cycle jump, which causes a constant error of $\pm 10 \mu s$ in TD.

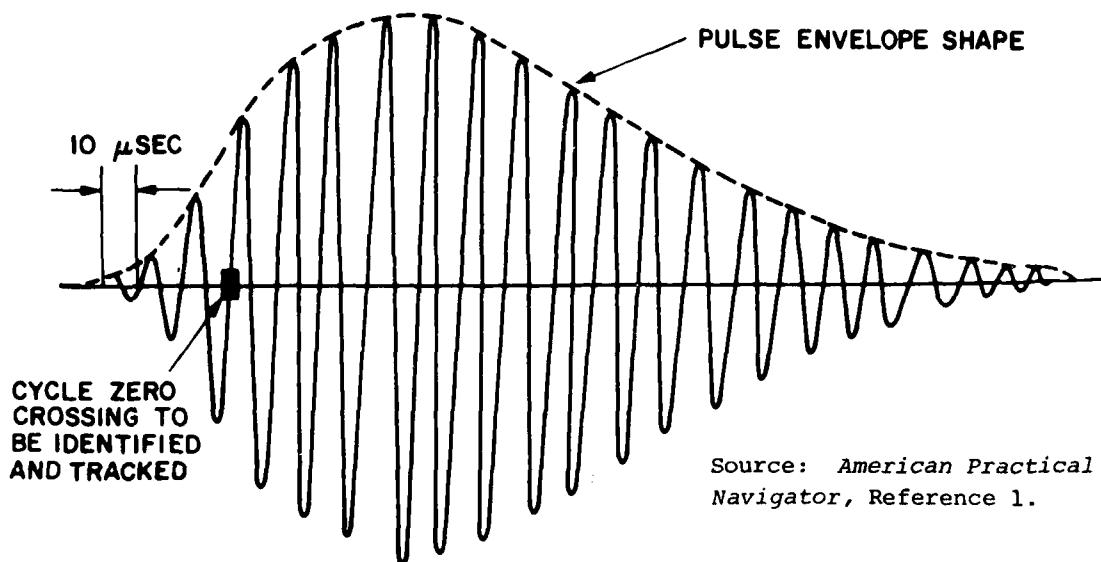


Figure A-3. SHAPE OF LORAN-C PULSE

Because the amplitude of the signal envelope at the third-cycle zero crossing is only about 50 percent of the peak value, multiple pulses (eight per group) are used so that more signal energy is available at the receiver to improve the signal-to-noise ratio without the necessity of increasing the peak transmitted power capability of the transmitters.

Loran-C uses ground waves instead of sky waves, because the stable nature of the ground wave is not affected by ionospheric fluctuations, which affect the propagation characteristics of sky waves. Contamination of the ground waves by sky waves is eliminated in Loran-C by use of the pulse transmission technique. Receiver reception of a sky wave is delayed between 33 and 1,000 μ s after reception of the ground wave. Sky wave reception with a minimum delay time is discriminated against by receiver sampling of the Loran-C transmission at the zero crossing point near 30 μ s of the start of the pulse. This technique results in full ground wave stability. Long-delay sky waves could perturb the integrity of the transmission by overlapping the ground wave of the succeeding pulse. To prevent this from happening, the phase of the 100 kHz carrier of each pulse is changed in accordance with a predetermined pattern referred to as a phase code.

Phase coding of the pulses within a group also provides a means of identifying chains of stations. The phase of the 100 kHz carrier of each pulse is either in phase or 180 degrees out of phase with a defined reference carrier in accordance with the assigned code. Different phase codes are defined for the master and secondary pulse groups to identify master and secondary stations. Two sets of phase codes are used for master and secondary pulse groups, alternating between successive GRIs so that the phase code changes with each GRI and repeats every other GRI.

1.4 Signal Processing

A position fix is established by the intersection of two or more hyperbolic lines of position (LOPs), each of which represents a constant range difference from two transmitters. Range differences are based on TDs. TD measurements between the receiver and at least three transmitting stations are necessary to establish a position fix. A signal propagation model is used in the process of determining range differences from the measured TDs.

Although Loran-C receivers are designed for processing of ground waves, a sky wave mode can be used when the receiver is beyond the reception range of Loran-C ground waves. Although use of sky waves provides less accuracy than use of ground waves, a single-hop sky wave can be received at distances from the transmitter of about 2,300 nautical miles (nm) -- nearly double the range of the ground wave. Use of Loran-C in the hyperbolic mode does not require a precision oscillator in the receiver for measurement of TDs, because synchronization of time references is maintained by the transmitting stations. Therefore, user clock bias does not affect the measurement of TDs.

Loran-C is also used to measure the actual time, rather than the TDs, required for signals to travel from each transmitting station to the receiver. This technique is referred to as the ranging mode, often called the range-range or rho-rho mode. In the ranging mode, each time measurement provides a circular rather than a hyperbolic LOP, which allows a position fix using two individual stations rather than two station pairs. Another advantage of the ranging mode is the elimination of the geometric dilution associated with the hyperbolic mode at extended ranges. Geometric dilution is a function of the user's relative position to the transmitting stations. The gradient, or spacing between consecutive LOPs per unit of time difference, such as 1 μ s, increases with the divergence of the hyperbolic LOPs. The effect is most pronounced along baseline extensions, which are beyond the two stations that define the end points of the baseline. When the gradient is high, a relatively low TD error will result in a relatively high position error. In the ranging mode, the gradient is a constant equal to the propagation velocity, thus eliminating geometric dilution. The ranging mode can therefore be used to extend the coverage area beyond that possible in the hyperbolic mode by overcoming the geometric dilution at extended ranges and by requiring the user to be within range of only two transmitting stations. Use of three stations enhances accuracy of position fix because redundant information is used to estimate errors.

All of these advantages of the ranging mode are seriously compromised by one disadvantage -- the need for a very precise and stable time reference in the receiver. The high cost of this type of equipment limits the use of the ranging mode for Loran-C navigation systems.

Before any navigation mode is used, the necessary signals must be acquired by the airborne receiver. The time required for signal acquisition

is typically thirty seconds to two minutes, with a maximum delay of five minutes -- depending on geometry, signal strengths, and the accuracy with which current position is known. Use of Loran-C in the hyperbolic mode requires three stations (a triad); the loss of any single station requires selection of a new triad. Although only three stations are used for navigation, continuous tracking of all stations in a chain eliminates the loss of time associated with signal acquisition when a new triad is selected. The eventual capability of using all signals from a chain for navigation will provide sufficient redundancy to ensure continual tracking stability and accuracy, even during station loss.

A back-up mode is available on most receivers to allow master independence when the master station fails. Loss of the master station automatically initiates the blink code on all stations in the affected chain, since the integrity of master-secondary TDs can no longer be ensured through monitoring. However, because each station uses an independent clock for synchronization to absolute time, it is reasonable to assume that inter-station synchronization will not degrade rapidly. A problem is encountered when trying to interpret the blink code. If only one station in a chain is blinking, it can safely be assumed that only that station has a problem and should not be used. If all stations are blinking, loss of the master is definitely indicated, but the level of integrity of individual stations is not obvious. However, if caution is used and signal parameters are monitored, the blinking signals can still be used for navigation.

Loran-C receivers are susceptible to localized interference created by such things as VLF transmitters, arc-welding operations, and 100 kHz communication channels carried on power lines. Notch filters can be used to minimize continuous wave interference from Decca navigation chains and communication stations within the same band, but they are not effective in eliminating broad-spectrum interference.

The achievable accuracy of Loran-C depends on a number of factors, including the following:

- Number of stations processed
- Signal quality
- Geometry of stations in relation to aircraft
- Definition of propagation model
- Region of operation

As a function of these factors, typical observed absolute accuracy ranges from a few hundred feet to a couple of miles. Repeatable accuracy is highly stable, usually within 100 to 200 feet.

The high degree of repeatability is an indication of the significance of the propagation model. With accurate modeling of the propagation characteristics, absolute accuracy can approach repeatable accuracy. Biases

result from the relative differences between the fixed propagation model and the actual propagation characteristics of the signals received from each station.

1.5 Operational Characteristics

Because Loran-C was initially implemented for marine use, it had some operational disadvantages that prevented acceptance for airborne navigation. Many of those disadvantages have since been eliminated through system modifications and improvements in user equipment. The Loran-C system was initially master-dependent, in that only the master of each chain had a clock to which each slave was referenced. If the master went off the air, the slaves lost their time reference, and the entire chain was out of operation. Independent synchronization to absolute time is now possible, since all stations are equipped with cesium clocks.

When Loran-C coverage provided only three stations in a given area, loss of any station led to system unavailability during hyperbolic navigation because of the lack of redundancy. The addition of more stations now ensures coverage from at least four stations in a given area.

Advances in user equipment have evolved from the necessity of TD overlay charts to today's fully automatic Loran-C RNAV systems. The advent of microprocessor technology has not only allowed for increased technical capability, but has also resulted in increased reliability and low cost.

The first airborne antennas used with Loran-C were tail cap and other electric dipole configurations. Signal loss and difficulty in reacquisition were significant problems because of the antenna's susceptibility to precipitation (P) static. The tail cap antenna also exhibited a null pattern problem. Use of H-field orthogonal loop antennas has resolved these problems.

2. OMEGA

2.1 History of Development

The Omega navigation system was developed to extend the range of a system like Loran-C to about 5,000 miles. For the past 25 years, the United States Navy has conducted intensive research and development for Omega. The first experimental Omega stations were established in Norway, Hawaii, Trinidad, and New York by 1964, when the Naval Research Laboratory conducted the first evaluation flights of a prototype airborne Omega receiver. Seven of the eight permanent Omega stations are now operational in Norway, Liberia, Hawaii, North Dakota, La Reunion, Argentina, and Japan; the last station, located in Australia, will become operational in mid-1981. A temporary station was operating in Trinidad until December 31, 1980. In July 1978, the United States Coast Guard assumed full responsibility for the operation and maintenance of United States-based Omega.

Until the eighth station is completed and resulting system accuracy and coverage can be measured and validated, the Omega network cannot be declared an operational system. However, coverage and accuracy of Omega are being verified on a regional basis.

2.2 Facilities

Omega stations transmit very low frequency (VLF) (10 to 14 kHz) continuous wave (CW) signals on a common carrier frequency on a time-shared basis. Except for the antenna, the complement of electronic equipment in each transmitting station is identical. The antenna system is either a vertical tower about 450 meters high supporting an umbrella of transmitting elements or a valley span typically 3,500 meters in length. Each Omega station has a transmission power of 10 kW. The major elements of each station are timing and control, transmitter, and antenna tuning.

Each Omega station synchronizes its transmissions with highly stable cesium-beam frequency standards, which are referenced to the atomic time scale. Monitor systems provide phase measurement data between stations. The data are used in an advanced optimal-estimation and control algorithm to provide corrections for any offset or divergence of a transmitter from mean Omega system time.

2.3 Signal Characteristics

All Omega stations transmit four frequencies (10.2, 13.6, 11.33, and 11.05 kHz) on a semicontinuous basis, with a basic repetition period of 10 seconds, in accordance with the format shown in Figure A-4. The notations f_1 through f_8 in the figure denote transmitted frequencies unique to each station, as follows:

$$\begin{array}{lll} f_1 = 12.1 \text{ kHz} & f_4 = 13.1 \text{ kHz} & f_7 = 13.0 \text{ kHz} \\ f_2 = 12.0 \text{ kHz} & f_5 = 12.3 \text{ kHz} & f_8 = 12.8 \text{ kHz} \\ f_3 = 11.8 \text{ kHz} & f_6 = 12.9 \text{ kHz} & \end{array}$$

The 0.2-second interval between successive transmissions eliminates the possibility of overlap of signals received from different stations and allows for a margin of error in alignment of the receiver commutator. The Omega signal format was designed so that each station could be identified by the transmission of a particular frequency at a prescribed time.

2.4 Signal Processing

Position determination for Omega can be obtained by either the hyperbolic or circular (ranging) technique. Hyperbolic systems utilize phase differences so that any drift in the local oscillator will affect both phase measurements equally and will therefore be canceled. Therefore, a high-precision oscillator reference is not required for the hyperbolic mode. The ranging mode requires individual phase measurements rather than phase differences. The level of precision required in the receiver oscillator is determined by the mode of operation in which it will be used.

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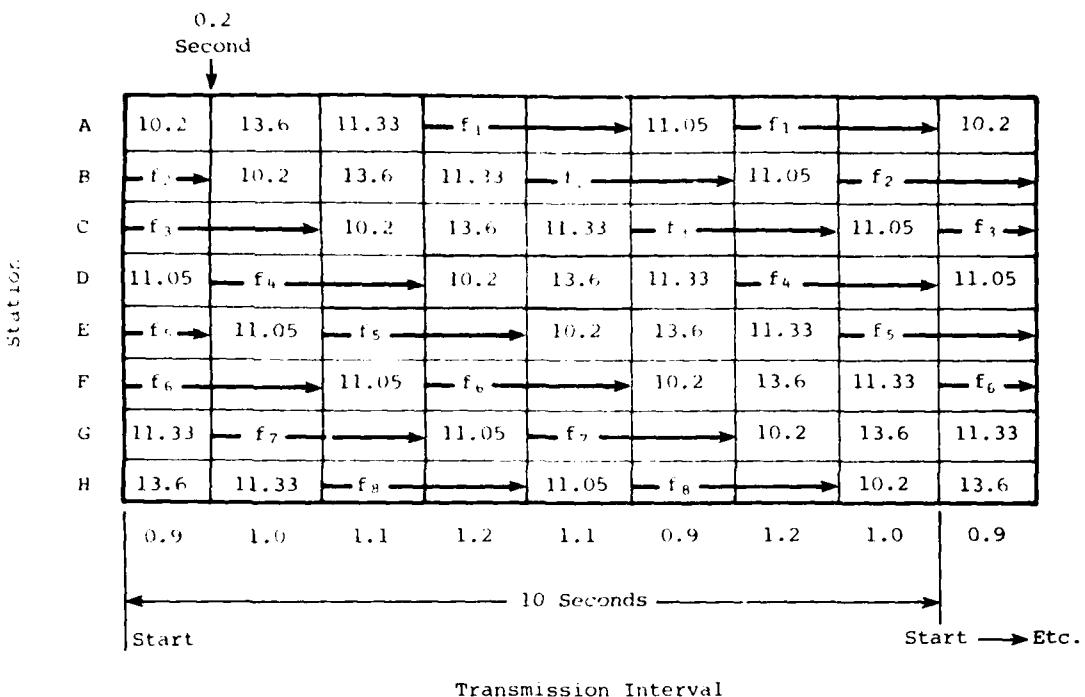


Figure A-4. SIGNAL FORMAT FOR OMEGA

2.4.1 Ranging Mode

Several methods of position determination can be implemented in the ranging mode. The rho-rho method involves direct measurement of the phase from only two stations. The intersection of the circular LOPs resulting from the phase measurements of the two stations defines position. The ambiguity caused by the existence of two points of intersection is resolved by proper initialization. Since there is no redundant information available for monitoring errors, the local oscillator must be highly precise -- preferably of the atomic standard type -- to achieve acceptable accuracy and reliability. In addition, because each phase measurement is used directly, the system is more susceptible to propagation anomalies, which are unpredictable.

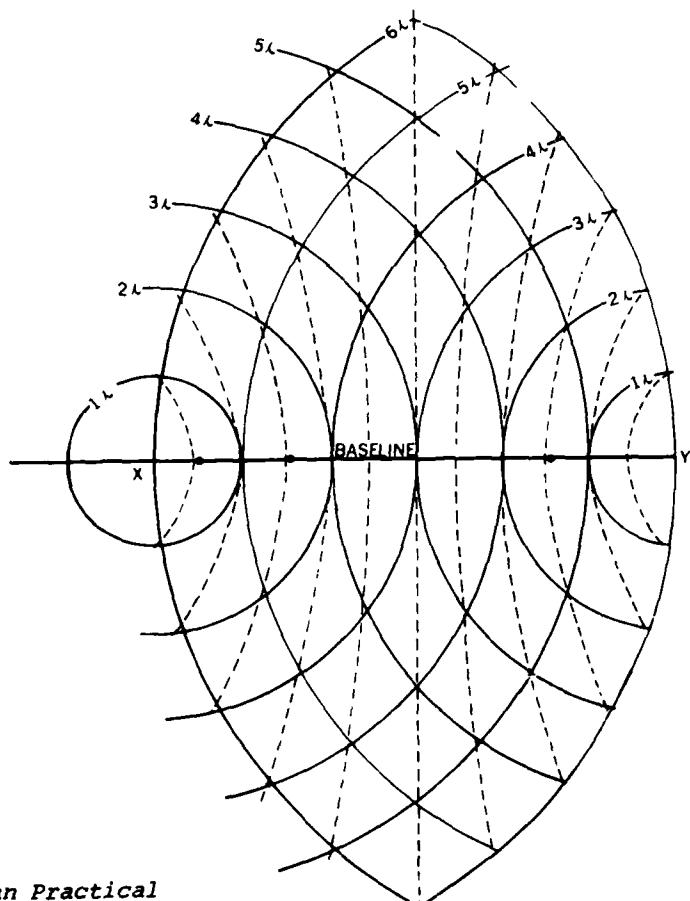
Use of three stations in a rho-rho-rho mode provides sufficient redundancy to permit limited self-calibration of the local oscillator. However, the assumption that any discrepancy in all LOPs meeting at a single point is wholly the result of oscillator drift may not be correct.

2.4.2 Hyperbolic Mode

Position fixing for Omega in the hyperbolic mode involves comparison of phase values obtained from signals of several transmitting stations. Loran-C provides hyperbolic LOPs defined by differences between the arrival times of signals from two transmitters. With Omega, hyperbolic LOPs are formed by contours of constant phase differences in the signal fields of

the transmitting stations. All points along a given contour have the same difference in distance from the two transmitting stations.

Identical phase angles emanating from each transmitter are repeated at every wavelength of the transmitted signal. Therefore, the same difference in phase angles occurs at the intersection of all integral-wavelength wavefronts radiating as circles from each transmitting station. The locus of these intersections is a hyperbolic contour of constant phase, called an isophase contour. The midpoint of the hyperbolic isophase contour line segment joining two points of intersection is a half wavelength from either wavefront; since it is part of the isophase contour, it also has the same difference in phase angles as at the intersections of integral wavefronts. Thus, identical phase differences repeat not only every wavelength, but every half wavelength, as illustrated in Figure A-5.



Source:
American Practical
Navigator, Reference 1.

Figure A-5. ISOPHASE CONTOURS

2.4.3 Laning

In the ranging mode, all circular LOPs spaced one wavelength apart correspond to the same phase angle measurement. Phase differences, the form of measurement in the hyperbolic mode, repeat along the baseline at intervals of a half wavelength. The repetition interval distance defines an Omega lane.

A representative baseline in the Omega system is about 5,000 nm in length. At a signal frequency of 10.2 kHz, with a propagation velocity of 161,829 nm per second, there are approximately 315 wavelengths. Thus 5,000 divided by 315 results in lane widths of approximately 16 nm for the ranging mode. Since lane widths in the hyperbolic mode are defined by intervals of a half wavelength, the lane widths along the baseline in the hyperbolic mode are approximately 8 nm. Divergence of the hyperbolic contours causes lane width in the hyperbolic mode to increase as a function of distance from the baseline.

Each lane between transmitting stations is numbered for identification. To aid in establishing position within a lane, phase measurements are expressed as the percentage of a cycle, with each 360 degrees constituting 100 centicycles. The difference between phase measurements in centicycles is numerically equal to the percentage value of the lane defining the LOP, generally expressed as centilanes. An observed phase difference corresponds to an LOP in each lane for a given station pair (600 to 700 lanes at 10.2 kHz in the hyperbolic mode). This ambiguity is overcome by initialization of the Omega receiver to current position accurate to within ± 0.5 lane-width and continuous count of lane changes resulting from vehicle motion. For the example of 10.2 kHz, initial position must be known to within ± 4 nm (± 8 nm in the ranging mode).

The four frequencies used for Omega navigation (10.2, 13.6, 11.33, and 11.05 kHz) provide lane widths ranging from 6 to 8 nm in the hyperbolic mode. Additional frequencies can be formed to yield coarser lane widths by "beating" together Omega signals on two different frequencies. As an example, combined processing of 10.2 kHz and 13.6 kHz signals yields a phase difference value of 3.4 kHz, resulting in a hyperbolic mode lane width of 24 nm. The net effect is a relaxation of required initial position accuracy to only ± 12 nm. Table A-1 shows the various lane widths possible with multiple frequency techniques for both hyperbolic and ranging modes of processing.

2.5 Propagation Modeling

Accuracy, and therefore practicality, of the Omega system depends on the inherent stability and predictability of the phase variations of a VLF signal over a very long propagation path. Propagation models characterizing VLF signals propagating in the earth-to-ionosphere waveguide are generally based on one of the following three approaches: hop theory, zonal harmonic series, and mode theory. Hop theory assumes that the VLF signal is composed of a ground wave in addition to a series of "hops" (or rays) generated by successive reflections between the ionosphere and the

Table A-1. INITIAL POSITION ACCURACY DETERMINATION FOR DUAL-FREQUENCY OMEGA

Frequency 1 (kHz)	Frequency 2 (kHz)	Frequency Difference (kHz)	Lane Width (nm)		Initial Position Accuracy Requirements (±nm)	
			Hyperbolic*	Ranging	Hyperbolic	Ranging
10.20	--	10.20	7.94	15.88	3.97	7.94
11.05	--	11.05	7.33	14.66	3.67	7.34
11.33	--	11.33	7.14	14.28	3.57	7.14
13.60	--	13.60	5.95	11.90	2.98	5.96
10.20	13.60	3.40	23.80	47.60	11.90	23.80
10.20	11.33	1.13	71.61	143.22	35.81	71.62
10.20	11.05	0.85	95.20	190.40	47.60	95.20
11.05	13.60	2.55	31.73	63.46	15.87	31.74
11.05	11.33	0.28	288.98	577.96	144.49	288.98
11.33	13.60	2.27	35.65	71.30	17.83	35.66

*Along baseline.

earth. The zonal harmonic series approach applies rigorous mathematical analysis to the physical interpretation of hop theory. Mode theory describes the total signal at any point within the waveguide in terms of the natural or characteristic modes of propagation. The prediction models used by Omega Navigation Systems Operations Detail (ONSOD) are based on the mode theory approach. Omega signal coverage diagrams are generated by predicting signal-to-noise ratio (SNR) and occurrences of excessive mode interference. Global computations of predicted phase corrections are used to develop predicted propagation corrections (PPCs), which are published in tables to provide phase corrections for various regions, times of day, and month.

The prediction models use propagation characteristics that are fairly well understood and highly repeatable. The most obvious influence on Omega signals is the effective height of the ionosphere. Increases in solar radiation advance ionization of the atmosphere, thereby effectively lowering the height of the ionosphere to about 70 km soon after sunrise; at night, the height is about 90 km. Because Omega phase is inversely proportional to phase velocity, the phase increases or decreases in step with the effective height of the ionosphere, referred to as diurnal phase shift.

The phase of the Omega signal received at a given point in space is determined by the phase velocity and distance to the source. If distance is held constant and phase velocity is increased, the previously measured phase will appear to have advanced beyond the given point in space, creating the impression that the point has moved closer to the transmitter.

Numerous other phenomena that influence signal propagation cannot be wholly taken into account because of their unpredictable nature. Geophysical parameters that affect propagation include ground conductivity, the earth's magnetic field, solar activity, latitude, and solar zenith angle. Sudden phase anomalies (SPAs) produced by sudden ionospheric disturbances (SIDs), and polar cap absorption (PCA) resulting from polar cap disturbance (PCD) are random and unpredictable, but occur more frequently during years of peak solar activity. A significant SID can cause position errors of about 2 to 3 nm, while a severe PCD could result in a position error of 6 to 8 nm, lasting for several days.

Another source of Omega signal error is modal interference, created by phase errors from additional ground and sky waves combining with the primary wave. This form of interference is minimized by automatic deselection of a station within a defined distance from the Omega receiver. This distance varies from 300 nm to 600 nm, depending on the equipment used. Beyond the prescribed distance, the limitation on range of ground and sky waves dilutes their impact on the primary wave.

The prediction models applied to the Omega system are based on monitor data taken for at least one year to fully exploit annual correlation. Therefore at least this amount of time will be required following completion of the Australian station before Omega can be declared a fully operational navigation system.

2.6 Operational Characteristics

Use of all available Omega frequencies can provide greater accuracy in determination of position. Since each frequency propagates through the air with different characteristics, off-nominal conditions will not affect all frequencies the same way. These off-nominal conditions can therefore be isolated, and their effects can be compensated for, by proper filtering of multiple frequencies.

Even more important to accuracy than the number of frequencies processed is the number of Omega stations within reception range and their geometry in relation to the aircraft receiver. Hyperbolic navigation requires a minimum of three stations at all times, while navigation in the ranging mode can be accomplished with only two stations and a sufficiently accurate local oscillator. The best geometry for greatest accuracy results when the LOPs intersect at right angles. This configuration provides equal cross-track and along-track accuracy. As the LOPs approach a parallel configuration, the resulting accuracy in position fixing is correspondingly degraded. When more than three Omega stations can be received, sufficient redundancy exists to provide excellent accuracy. Generally good Omega signal coverage throughout the continental United States provides availability of a minimum of three stations. When an aircraft encounters loss of Omega signals, preventing satisfactory Omega navigation, the area in which this condition persists is referred to as a "hole" in signal coverage.

As was mentioned earlier, the Omega transmission format repeats every 10 seconds, with each Omega station transmitting different frequencies at any given time. It would therefore require a full 10 seconds to receive all transmitted frequencies from all Omega stations. As a result, when all phase information is processed to determine position, some information is no longer current, but is up to 10 seconds old. This loss of processing time synchronization is overcome by projecting each signal forward in time in accordance with its respective position in the processing cycle. This form of processing constitutes a dead reckoning system with ground-referenced updates. The dead reckoning system uses aircraft heading and speed information (with the ground-referenced updates) provided by the Omega system. Aircraft heading and speed information can be supplied by on-board sensors or manual data entries or can be derived from progressive Omega measurements.

When Omega measurements are used to estimate aircraft heading and speed, filter time constants of sufficiently long duration must be employed to minimize unwanted deviations resulting from noise and other spurious activity. A common predicament encountered in establishing a filter time-constant is that, while stability can be achieved with use of a long time-constant, quick response to maneuvers requires a short time-constant. Since the most prevalent use of Omega is for en route navigation with minimal heading or speed changes, a long time-constant has generally been preferred and is therefore the standard for Omega receivers. With increased use of Omega in the airborne environment, however, there is greater interest in the possible use of Omega in approach operations, where a great deal of maneuvering can occur. Acceptance of Omega for approach navigation will be predicated on the ability of the airborne Omega navigation system to respond

quickly (a short filter-time-constant) and accurately to course and speed changes.

Omega antennas are of either the E- or H-field type. The H-field antenna is an orthogonal loop that captures the magnetic (H-field) component of the signal. Various configurations of the H-field antenna have been designed to accommodate the many different installation requirements existing for both large and small aircraft. H-field antennas are desirable because of their immunity to the effects of precipitation static (P-static). However, since H-field antennas are designed for high sensitivity to magnetic fields, they are susceptible to magnetic noise.

On some aircraft, 400 Hz interference from power generation is so widespread that a suitable location for an H-field antenna cannot be found. In these cases, a capacitive (E-field) antenna is used. The E-field whip antenna is immune to magnetic noise but is susceptible to P-static.

Some manufacturers have offered custom antenna design to maximize antenna efficiency for the particular installation environment. One such design uses heading information to electrically orient an H-field antenna.

2.7 VLF Signal Processing

All Omega stations are VLF transmitters. There are additional VLF transmitters that are not part of the Omega system. The United States Navy maintains several VLF communication stations in various countries around the world to provide a worldwide military communications network. Although these stations were not intended to be used for navigation purposes, they are technically suitable for use as navigation aids. However, since the stations are not within the framework governing compliance with international navigation standards, they are used solely for secondary mode navigation. VLF stations provide a means of navigating through regions of unacceptable Omega coverage without the necessity of reverting totally to dead reckoning. VLF can be implemented as the sole signal source or can be used in combination with Omega signal processing. In general, when the VLF mode is activated, one of the Omega frequency channels is deactivated, and the VLF signals are superimposed in a fixed sequence in the Omega transmission time slots of the deactivated Omega frequency channel. The phase of the VLF signal is initialized at the position of the receiver at the time the VLF station signal is first received. Subsequent phase measurements indicate position change.

The operational capabilities of Omega navigation systems heavily influence the potential accuracy of position fixing. Table A-2 presents some typical expected accuracies as a function of operational capability.

**Table A-2. OPERATIONAL CAPABILITY VERSUS
EXPECTED ACCURACY FOR OMEGA
NAVIGATION SYSTEM**

Number of Stations Received	Number of Frequencies Processed	VLF Processing	Accuracy of Position Fixing (nm)
0	0	X	<u><4</u>
2	3	X	<u><2</u>
>4	4	--	1 to 1.5
>4	3	X	1 to 1.5

3. VOR

3.1 History of Development

VHF Omnidirectional Range (VOR) was developed in response to the growth in air traffic in the 1930s. The unpredictable propagation characteristics of the low and medium frequency range navaids in use at that time severely limited their practical service area. As aircraft began flying at higher and higher altitudes, line-of-sight distances increased, making VHF frequencies useful to over 100 miles. The only directional guidance navaid available before VOR that did not require a direction finder on board the aircraft was limited to selection of one of four courses. VOR became the United States standard in 1946 and the international standard in 1949, combining communication and navigation within one band.

3.2 Facilities

The VOR ground station transmits two 30 Hz signals -- one is a constant phase omnidirectional reference signal, while the second signal varies in phase in relation to the magnetic bearing of the aircraft from the VOR station.

VOR antenna systems use Alford loops, which generate horizontally polarized signals with the same field pattern as a vertical dipole. Conventional VOR systems use four Alford loops arranged in a square. The plane containing the Alford loops is horizontal and located a half wavelength above a circular and conducting ground plane, or counterpoise, that is approximately 30 feet in diameter. The counterpoise also acts as the roof of the transmitter house, with the loops protected from the weather by a radome. The radome is generally hemispherical in shape; if a Tactical Air Navigation (TACAN) antenna is included in a VOR installation (a VORTAC), the radome is conical. The VOR antenna system is designed to operate in two distinct modes, corresponding to the two distinct signals radiated -- the carrier mode and the sideband mode, described in the following section.

3.3 Signal Characteristics

VOR operates in the VHF band of 108 MHz to 118 MHz, divided into 50 kHz channels. Originally, the channel width was 100 kHz. The 30 Hz reference signal is generated by frequency modulation of a 9.960 kHz subcarrier signal, which amplitude modulates the radio frequency (RF) carrier signal. This reference signal is radiated when the antenna is operated in the carrier mode, where all four loops are simultaneously driven in phase with carrier frequency currents, resulting in an omnidirectional pattern. The variable phase signal is generated when the antenna is operating in the sideband mode which causes each diagonal pair of loops to be excited so that at any instant of time the horizontal plane pattern of each pair of loops above the counterpoise is a figure eight. The relative phase between the pairs of loops is such that the combined effect of these phases in space produces a single figure eight azimuthal pattern rotating at 30 revolutions per second. Combination of the carrier field with the total sideband field radiates a cardioid pattern that rotates at 30 revolutions per second, generating a 30 Hz sine wave at the output of the airborne receiver. The 30 Hz reference signal and the rotating pattern sine wave are synchronized so that they are exactly in phase when viewed from magnetic north. Therefore, the phase between the reference and the rotating cardioid varies directly with the bearing of the aircraft.

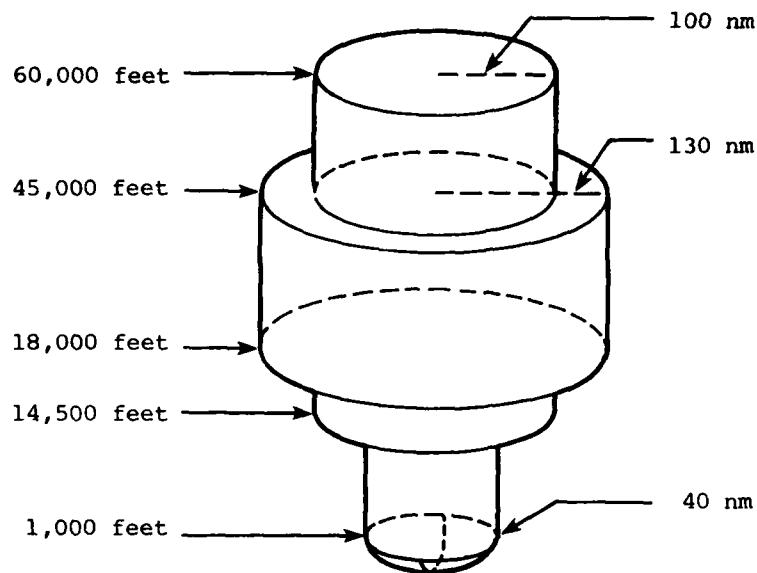
VOR signal reception depends on the standard service volume of the class of facility used and can range in radial distance from 40 nm to 130 nm from the VOR, depending on altitude, as shown in Figure A-6. The primary difference between Figure A-6 and the currently existing specifications for standard service volumes as defined in FAA Advisory Circular (AC) 00-31 (U.S. National Aviation Standard for the VORTAC System) is the FAA-proposed additional stipulation of a defined coverage area between 1,000 and 14,500 feet altitude for the high-altitude station.

3.4 Signal Processing

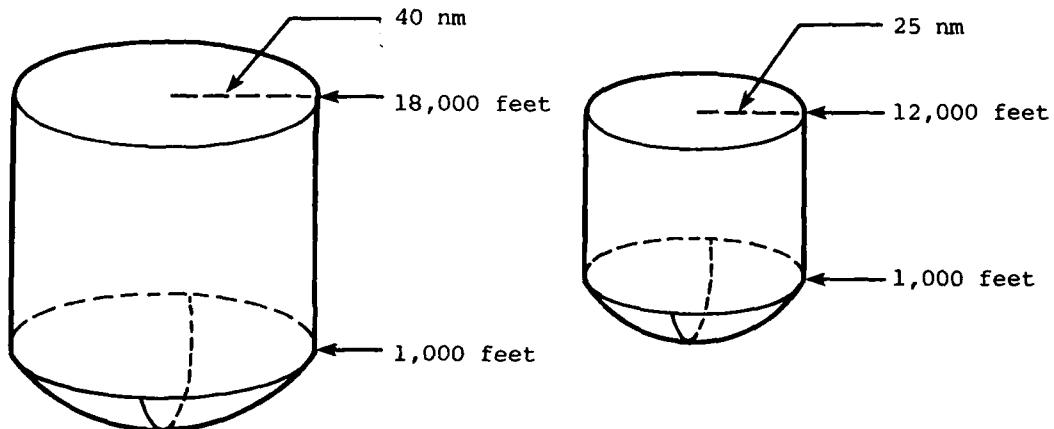
The airborne receiver detects the VOR signal and passes it through an amplitude modulation (AM) detector. The AM detector distinguishes the identity tone and any voice frequencies present and broadcasts them through the aircraft audio system. These components of the signal are removed via a 30 Hz filter, and the resulting 30 Hz amplitude modulation produced by the rotating pattern of the VOR is fed to phase comparison circuitry. The original signal is also passed through a 9.960 kHz filter, a limiter to remove 30 Hz amplitude modulation, and a frequency modulation detector, which then outputs the 30 Hz frequency-modulated reference. After one more stage of filtering, the reference frequency is compared with the variable phase signal in the phase comparator. The output of the phase comparator is the bearing of the aircraft with respect to magnetic north.

3.5 Operational Characteristics

Use of VHF eliminates sky wave contamination of VOR signals and prevents interference from stations beyond line of sight. The most significant error sources are site errors and errors in measuring phase shifts at 30 Hz.



Standard High-Altitude Service Volume



Standard Low-Altitude Service Volume

Standard Terminal Service Volume

Source: FAA Order 9840, Reference 13.

Figure A-6. VOR STANDARD SERVICE VOLUMES

Site errors are caused by multipath effects at the ground station, resulting from signal reflections off of trees, buildings, and other scattering objects near the transmitter. The multiple signal paths created by the reflections combine with the desired signals to alter the phase difference measured at the aircraft. This results in an error in the VOR bearing indicated by the airborne receiver. As the aircraft moves, the phase difference between the desired signal path and the reflected paths changes. The phase difference error fluctuates with a measurable frequency depending on the rate of change of path difference. This phenomenon, referred to as scalloping, becomes more pronounced with decreasing distance from the VOR. Coverage of VOR is restricted because of line of sight limitations. The coverage pattern of a VOR is additionally restricted by a limited elevation-angle of transmission, above which no VOR signal is available. VOR signals currently are guaranteed to be available within 60 degrees of elevation from the ground plane of the transmitter. In practice, however, signals can generally be received up to an elevation angle of nearly 80 degrees. The airspace directly above the VOR in which no signal exists defines a cone, the apex of which is at the transmitter with a central angle of 60 degrees. This cone, generally referred to as the cone of confusion, is illustrated in Figure A-7. As can be seen from the figure, the effective area of the cone increases with altitude. At 5,000 feet altitude, the area of concern above the VOR has a radius of 0.4 nm. At an altitude of 30,000 feet, the radius is 2.5 nm.

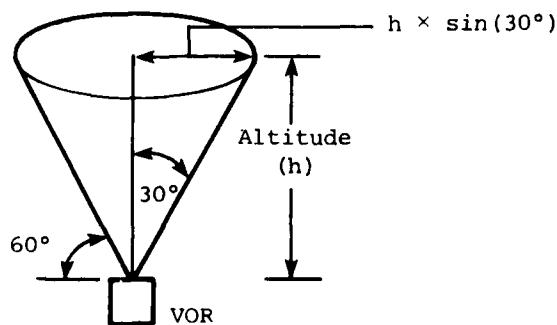


Figure A-7. VOR CONE OF CONFUSION

4. DME

4.1 History of Development

Distance measuring between aircraft and ground stations is provided through Distance Measuring Equipment (DME) and Tactical Air Navigation (TACAN). Since TACAN uses the same pulses and frequencies for distance measurement used by the standard DME system, all references to the operational design and performance of DME correspondingly apply to TACAN.

The history of DME dates back to the Rebecca-Eureka pulse ranging system developed during World War II, which operated at 200 mHz. By international agreement in 1946, DME was assigned for operation in the 960 to 1,215 mHz L-band. The exact frequencies and pulse techniques were not established until 1959, however.

4.2 Facilities

Ground-based DME consists of a receiver-transmitter and an antenna. DME is typically collocated with some other navigational aid, including the following station types:

- VOR/DME
- ILS/DME
- TACAN
- VORTAC

VOR/DME is a DME station located at the same site as a VOR station. ILS/DME denotes the presence of a DME at the site of an instrument landing system (ILS). TACAN provides both azimuth and distance information to suitably equipped aircraft. Although the azimuth signal from a TACAN is not the same type as from a VOR, the distance measuring function of TACAN is equivalent to DME. A VORTAC facility consists of a VOR station collocated with a TACAN station.

4.3 Signal Characteristics

The receiver/transmitter channels of DME stations located with a VOR station are paired with the respective VOR channel in accordance with a published table. The air-to-ground transmitted frequencies of DME are from 1,025 to 1,150 MHz, while the ground-to-air transmitted frequencies are from 962 and 1,213 MHz. The VOR frequencies with which DME frequencies are paired are between 108 MHz and 118 MHz. VOR frequencies are divided into 100 kHz-wide channels, resulting in 100 channels. There are 126 DME channels between 1,025 and 1,150 MHz, spaced 1 MHz apart, allowing frequency pairing with the 100 VOR channels and leaving 26 unpaired DME channels. When the VOR channel width was changed to 50 kHz, an additional 100 VOR channels were made available, bringing the total to 200. As a result of this action, additional DME channels were made available by the designation of X and Y channels. The frequency spacing between DME channels was not changed.

X channels correspond to the original 100 kHz-spaced VOR frequencies and the corresponding DME frequencies. Spacing of the ground reply pulse for X channels is 12 μ s. VOR channels that are offset 50 kHz from the X channels are designated Y channels; they have a ground reply pulse spacing of 30 μ s. The airborne interrogating pulse-pair spacing is 12 μ s on X channels and 36 μ s on Y channels. With use of X and Y channels, 252 DME channels are available; 200 of these are paired with the available VOR

frequencies. The transmit and receive frequencies of any one channel are separated by 63 MHz.

DME ground stations are capable of handling approximately 100 aircraft interrogations simultaneously. When more than 100 aircraft interrogate the ground station, the ground station limits its sensitivity and replies only to the 100 strongest interrogations. Most airborne DMEs are designed to operate down to a reply efficiency of 50 percent, reflecting the situation where the DME receives replies to only half of its transmitted interrogations.

The ground station continuously transmits a squitter signal (filler signal) of 2,700 pulse-pairs per second (pp/s), with an identification code signal of 1,350 pp/s at 30-second intervals. When interrogated by the airborne DME pulse pair, the ground station transmits a reply pulse pair that replaces a squitter pulse pair 50 μ s after interrogation. Replies are considered valid by the airborne receiver when they occur at approximately the same time after every transmitted pulse pair. The pulse rate of the airborne DME transmissions is varied randomly (jittered) so that no two airborne DMEs are transmitting at the same rate. This jitter technique prevents transmitted pulse pairs from another aircraft DME being mistaken for reply pulses.

The airborne DME decreases the frequency of interrogations when it has established the validity and regularity of the reply pulses. These variations in level of frequency of interrogation are referred to as either the search mode or track mode -- the track mode indicates less frequent interrogation. Use of the track mode relieves the loading of the ground station to allow service of more aircraft.

The identification signal of 1,350 pp/s can be converted to an audio signal so that the pilot can monitor the signal to confirm that the airborne DME is tracking the station the pilot selected.

4.4 Signal Processing

The DME system employs a pulse-ranging technique whereby an airborne unit, referred to as an interrogator, transmits a pair of pulses that the DME ground transponder retransmits after a fixed time delay. Paired pulses are used to reduce interference from other pulse systems. The peak pulse power of the airborne unit is about 50 watts to 2 kilowatts. The DME ground station (or transponder) receives these pulses and, after a fixed delay of 50 μ s, retransmits them back to the aircraft on a frequency 63 MHz below or above the airborne transmitting frequency. The peak power of the ground station is between 1 and 20 kilowatts.

The airborne interrogator automatically compares the elapsed time between transmission and reception, subtracts the fixed delay of 50 μ s, and displays the result in terms of nautical miles. The range thus computed is slant range, the actual distance between the aircraft and the DME ground station, rather than ground distance. If the aircraft is more than one mile

from the station for each 1,000 feet of altitude, the difference between slant range and ground distance is negligible. Correction of slant range to obtain ground distance is a function only of altitude above the station.

4.5 Operational Characteristics

If the DME signal is lost after the track mode has been established, the DME retains the last value of distance computed for a nominal period of time. If the signal is not reacquired within this period, the airborne DME enters the search mode.

The most potentially serious problem encountered when DME is used is false lock-on. This occurs when the airborne DME acquires and tracks transponder replies to a multipath signal instead of the direct signal. "Confirm/track" circuits in the airborne unit eliminate the possibility of false lock-on by scanning the interval just before the tracked pulse pair to confirm that the tracked signal is not an echo. The magnitude of error caused by false lock-on can be several miles. Multipath and siting errors other than false lock-on are small and nearly random.

5. GPS

5.1 History of Development

The Navigation System using Timing and Ranging (NAVSTAR) Global Positioning System (GPS) is currently being developed and evaluated as an advanced satellite-based navigation system. Although it was originally scheduled to be operational in 1982, current estimates reflect an initial 18-satellite deployment by 1987.

The concept of NAVSTAR GPS, being developed by the Department of Defense, evolved from the 1973 merger of the Navy's Time Navigation (TIMATION) Program and the Air Force 621B Project. Both projects were established in the mid-1960s to investigate satellite-ranging techniques to satisfy military navigation requirements. The Air Force used ground stations to simulate satellite signals, whereas the Navy actually launched satellites.

The Navy TIMATION satellites provided more accuracy and greater coverage through use of ranging techniques than was possible through use of previously developed satellite navigation systems, such as TRANSIT, which were based on frequency measurements. TRANSIT is the Navy Navigation Satellite System (NNSS or NAVSAT) currently used primarily for navigation of submarines and surface ships, both civil and military.

When the Department of Defense's GPS Joint Service Project Office was created, the Air Force was given the responsibility of program management through the Space Division in El Segundo, California. The Navy established the Navigation Technology Program to provide technical support and design of the navigation technology satellites (NTSs) currently used to evaluate

the components and systems being developed for the navigation development satellites (NDSS) of NAVSTAR GPS.

5.2 Facilities

NAVSTAR GPS involves the following segments of operation, each dependent on the others to provide precision worldwide navigation capability:

- Ground control segment
- Space system segment
- User segment

The ground control segment tracks the satellites, monitors the navigation signals, and provides correction terms to the satellites. The space system segment includes the satellites themselves and the navigation signals they transmit. The user segment comprises numerous receivers representing diverse applications of the navigation data.

5.2.1 Ground Control Segment

The primary function of the ground control segment is to maintain the precision of the navigation data supplied to the user. This function is performed via a network of four monitor stations (MSs), an upload station (ULS), and a master control station (MCS). The four unmanned MSs are remotely located from but directly linked to the MCS. Each MS receives and decodes satellite navigation data and collects local meteorological data. Data from each MS are relayed to the MCS, where they are processed to determine satellite ephemeris and clock errors. The MCS then generates correction terms to compensate for identifiable biases and provides them to the ULS for upload transmission to the satellite.

The ability of GPS to provide highly accurate navigation capability depends on precision timing and frequency control. The importance of precision timing in terms of navigation accuracy is illustrated by the fact that one nanosecond of time error corresponds to 0.3 meter (0.984 foot) of distance error (assuming the speed of light to be 3×10^8 m/s).

The MCS maintains GPS system time through the use of cesium clocks. Because the precision of GPS system time must be continuous, it is therefore not offset by leap year seconds, which cause periodic adjustments to universal coordinated time (UTC). The MCS monitors the satellite clocks to determine their degree of synchronization with GPS system time. Clock corrections are uploaded by the ULS to the satellites and become part of the navigation message transmitted by the satellite to users.

5.2.2 Space System Segment

Great effort has been expended in the search for an optimal 18-satellite configuration. The most current, but not necessarily final, choice uses six orbital planes, with three satellites in each orbit. Each satellite orbits at 10,900 nm above the earth in a 12-hour period. The ascending nodes of

each orbit are equally spaced by 10 degrees in longitude around the equator. Each orbital plane is inclined by 55 degrees with respect to the equatorial plane, and the three satellites in each orbit are equally spaced by 120 degrees. The satellites are designed for an operating life of five years.

The four atomic clocks contained in each satellite are accurate to one second per 30,000 years. Two levels of navigation accuracy are provided by the GPS signals transmitted from the satellite. The greatest degree of accuracy is provided through acquisition of the precision code (P-code). Access to this code is limited to military users. A second code, the coarse acquisition (C/A) code, is less accurate; it will be made available to all users. The accuracy capability of the C/A code will be further degraded for reasons of national security.

5.2.3 User Segment

Several configurations of GPS user equipment are currently being developed and evaluated. They are as follows:

- X-set
- Y-set
- Z-set
- Manpack
- GPSPAC

The X-set was developed as a means to evaluate the speed and accuracy of GPS position-determination under the most severe jamming and dynamic conditions that might be experienced on high-performance military aircraft. The X-set uses four receiver channels, which enable it to process data from four satellites simultaneously. It receives GPS signals on two frequencies, allowing measurement of propagation errors.

The Y-set is more compact than the X-set and costs less. It has only one receiver channel and therefore sequences between satellites. Performance of the Y-set is comparable to that of the X-set except under conditions of high dynamics.

The Z-set is a low-cost, compact configuration that sacrifices high accuracy and dynamic response. As with the Y-set, the Z-set sequences between satellites, using only one receiver channel. But unlike the X- and Y-sets, which process two frequencies, the Z-set processes only a single frequency. Because the Z-set is able to acquire only the C/A code, it provides less accuracy than the X- and Y-sets, which can also acquire the P-code.

Although Manpack does not require high dynamic capability, it does require high accuracy, small size, low weight, low power, and antijam capabilities. Manpack is essentially the Z-set with the addition of dual frequency and P-code processing.

GPSPAC is intended primarily for use in satellites and shares the design features of the Z-set and Manpack.

The many possible applications of NAVSTAR GPS include the following:

- Strategic aircraft and cruise missile navigation
- Battlefield operations
- Submarine navigation (update of inertial navigation systems [INSSs] while surfaced)
- Tactical navigation
- Aircraft carrier navigation
- Harbor and sea lane operations
- Maritime shipping
- Search and rescue operations
- Spacecraft operations
- Surveying operations
- Oil exploration
- Air traffic control
- Civil air navigation

5.3 Signal Characteristics

5.3.1 Modulation

The signal transmitted by the satellite to the user is modulated by a sequence of bits that follow a pattern unique to each space vehicle. These patterns are referred to as pseudorandom noise (PRN) codes. PRN codes exhibit the characteristics of random thermal noise until the pattern is decoded and the receiver locks onto it. The signals are coded for two reasons. The first is to allow denial of access to the signal by withholding details of the code patterns. The user receiver must be able to match the incoming code to establish a lock-on. The second reason for using a code is so that when the sequence generated by the user receiver is matched with the incoming signal, measurement of the phase shift required to maintain match of the codes provides a measurement of the transit time of the navigation signal.

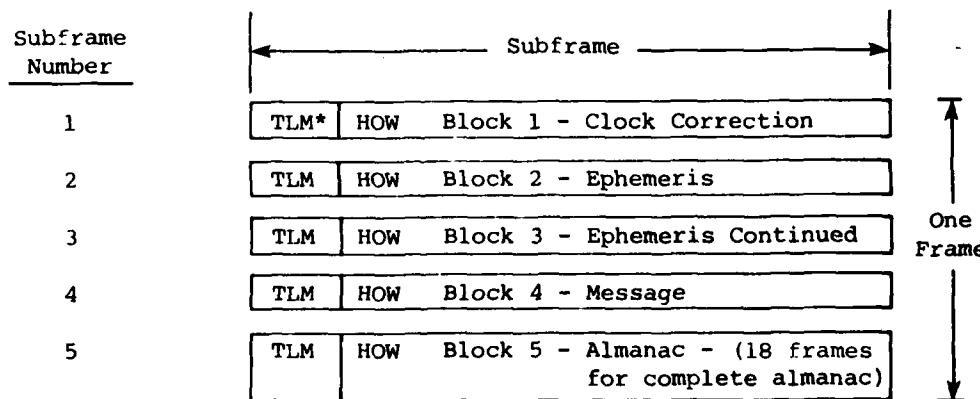
Two forms of PRN codes are used to modulate the NAVSTAR GPS navigation signal. The first and most precise PRN code is the precision code (P-code). The precision navigation accuracy attained from use of this code is made possible by its transmission rate of 10.23 megabits per second, or 97.8 nanoseconds per bit. At the speed of light (3×10^8 m/s), each bit of the P-code corresponds to a distance resolution of 29.34 meters (96.8 feet). However, the repetition rate of the P-code pattern is only once per seven days, making it effectively impossible to lock onto it without knowledge of the code pattern. Even with such knowledge, aiding is generally required

for rapid convergence on pattern synchronization. For this reason, a second PRN code is used -- the coarse acquisition or clear access (C/A) code. The C/A code repeats itself every millisecond, enabling easy acquisition and lock-on. The transmission rate of the C/A code is one-tenth that of the P-code, resulting in a distance resolution of 293.4 meters (968 feet). By locking onto the C/A code, the receiver can extract the navigation information contained in the signal. Included in the navigation message is a parameter referred to as the handover word (HOW), which is used in transferring from the C/A code to the P-code.

5.3.2 Format

The navigation message contains the handover word, data relating to space vehicle (SV) status, clock correction parameters, corrections for signal propagation delays, the ephemeris of the SV whose signal is being received, and almanac information that defines the approximate ephemerides and status of all other space vehicles.

The navigation message is contained in a 1,500-bit, 30-second data frame. The data frame is subdivided into five subframes, each of which contains 10 words, each word 30 bits in length. The first two words of each subframe are a telemetry word (TLM) and the C/A-to-P-code HOW. The TLM serves as an identifier to facilitate pattern synchronization and contains information primarily for use by the ground control segment, relating to upload operations. The HOW contains information that allows transition from the C/A code for users with access to the P-code. The remaining eight words in each subframe constitute a block of data, as illustrated in Figure A-8.



*TLM - Telemetry word.

HOW - Handover word.

Figure A-8. DATA FRAME FORMAT FOR GPS

Block 1, corresponding to subframe 1, contains the SV clock correction parameters and ionospheric propagation-delay model parameters. Blocks 2 and 3 contain the ephemeris of the SV. Block 4 is reserved for special alphanumeric messages, and Block 5 contains almanac data for all space vehicles. Only a single SV almanac is available per data frame. Therefore, it takes 18 frames, nine minutes, for the receiver to cycle through the almanac for a system complement of 18 satellites. The almanac information is required for use in signal acquisitions, while the other information is necessary for accurate processing of the navigation signal.

5.4 Signal Processing

As previously mentioned, each satellite generates a particular C/A code. The user receiver generates replicas of these codes and cross-correlates the locally generated signals with the signals received from the satellites. A tracking loop is used to establish synchronization between the two signals. Tracking error is indicated by the output of the correlator, with minimum error representing the peak of the autocorrelation function. Maximum code tracking is achieved by advancing and retarding the phase of the locally generated signal with respect to user clock timing. If the user clock is synchronized to GPS system time, the time delay associated with the phase difference measured at a common clock time between the local and received signals indicates the travel time of the signal between satellite and receiver. The travel time measured corresponds with satellite-to-receiver range.

In reality, the quality of the user clock is not high enough to maintain synchronization to GPS system time. Therefore, the time, or range, measurement includes clock bias errors and is referred to as a pseudorange measurement.

By measuring range from any individual satellite, the user places himself on a sphere centered at that satellite. Two range measurements create two spheres, the intersection of which defines a circular LOP. The intersection of a third sphere under ideal circumstances would provide a singular point of intersection and thereby a relative position fix with respect to the center of each sphere. Knowledge of the earth-referenced X, Y, and Z position coordinates of each sphere center -- that is, each satellite -- would result in a three-dimensional fix of user position.

Satellite position can be accurately computed from the ephemeris parameters included in the navigation message of the received GPS signal. Data contained in the message are accessible once the format identifiers have been detected after track lock-on.

Although three satellites generate three spheres, they do not provide an accurate three-dimensional position fix. The clock biases included in the pseudorange measurements introduce errors into the navigation computations. Each pseudorange measurement is therefore composed of the three position parameters and a clock bias term. The existence of four unknowns requires four pseudorange measurements to obtain four equations, which can then be solved for the position in three dimensions and the user clock offset.

Before the four equations are simultaneously solved, however, each pseudorange measurement is compensated for ephemeris errors, propagation delay, and satellite clock offset. The terms providing these corrections are included in the navigation message. Additional accuracy can be achieved when the accumulated phase difference between the received signal and the locally generated reference code is measured over a fixed time interval. This delta range measurement has the accuracy and resolution of a fraction of the carrier wavelength.

The GPS signal from each satellite is transmitted over two carrier frequency links, both of which are in the lower microwave region called the L-band. Link 1 (L1) has a center frequency of 1,575.42 MHz, and Line 2 (L2) has a center frequency of 1,227.60 MHz. When the two frequencies are processed, propagation errors that vary with frequency can be identified, and appropriate corrections can be generated and applied. L1 currently carries both the C/A code and the P-code, whereas L2 carries only the P-code. Inability to process the C/A code on two frequencies prevents the civilian user receiver from determining propagation errors. However, propagation corrections available in the navigation message do improve the accuracy of the single-frequency signal processing.

5.5 Operational Considerations

It was stated earlier that four range measurements are necessary to obtain a three-dimensional position fix. This requirement for a minimum of four satellites to be visible at all times throughout the world is difficult to satisfy with only 18 satellites. Failure of a single satellite would result in a large area of the United States not having coverage by four satellites during certain times of the day. As an alternative to the severe degradation of accuracy resulting when clock biases cannot be accounted for via the fourth range measurement, an altimeter can be used to supply the Z (vertical) component of the range equations. Any inaccuracies in the vertical measurement will translate into lateral and longitudinal position errors. Although barometric altimeters provide satisfactory relative accuracy, they are a poor substitute for the fourth satellite in terms of absolute position measurement. The usefulness of altimeter aiding is further limited because of satellite/user geometry. Studies have indicated that the altimeter measurement and one of the satellite range measurements would generally lie in the same plane with the user, seriously diluting the effectiveness of the measurement.

APPENDIX B

EQUATIONS

This appendix contains the equations used to obtain the values of navigational errors specified in this report.

1. DEFINITION OF TERMS

ϕ_1 = Latitude of origin in degrees

λ_1 = Longitude of origin in degrees

ϕ_2 = Latitude of destination in degrees

λ_2 = Longitude of destination in degrees

$$\bar{\phi} = \left(\frac{\phi_1 + \phi_2}{2} \right)$$

$$DLo = \lambda_2 - \lambda_1$$

DLox = Interval of longitude measured from point of departure in degrees

2. RHUMB-LINE EQUATIONS

Rhumb-line course angle (α in degrees):

$$\alpha = \tan^{-1} \left(\frac{\phi_2 - \phi_1}{DLo \cos \bar{\phi}} \right)$$

Latitude of points on the rhumb-line track (ϕ_{RL} in degrees):

$$\phi_{RL} = \phi_1 + DLox \cos \alpha \tan \alpha$$

Rhumb-line distance (R in nautical miles):

$$R = 60 \sqrt{[(\phi_2 - \phi_1)^2 + (\text{DLo} \cos \bar{\phi})^2]}$$

3. GREAT-CIRCLE EQUATIONS

Initial great-circle course angle (C in degrees):

$$C = \tan^{-1} \left[\frac{\sin(\text{DLo})}{\cos\phi_1 \tan\phi_2 - \sin\phi_1 \cos(\text{DLo})} \right]$$

Latitude of the great-circle vertex (Lv in degrees):

The vertex of a great circle is defined as the point of greatest latitude.

$$Lv = \cos^{-1} [\cos\phi_1 \sin(C)]$$

Difference of longitude between the vertex and the point of departure (Dlov in degrees):

$$Dlov = \sin^{-1} \left[\frac{\cos(C)}{\sin(Lv)} \right]$$

Latitudes of points on the great-circle track (ϕ_{GC} in degrees):

$$\phi_{GC} = \tan^{-1} [\tan(Lv) \cos(Dlox - Dlov)]$$

Great-circle distance (D in nautical miles):

$$D = 60 \times \cos^{-1} [\sin\phi_1 \sin\phi_2 + \cos\phi_1 \cos\phi_2 \cos(\text{DLo})]$$

4. GEODESIC ERROR EQUATIONS

Difference between a spherical-earth model and a Clarke 1866 ellipsoid model:

$$E_x = \left[9.12951 \cos \bar{\phi} - 2.92495 \cos(3\bar{\phi}) \right] (\lambda_2 - \lambda_1) \left(\frac{\pi}{180} \right)$$

$$E_y = 0.37414 (\phi_2 - \phi_1) \left(\frac{\pi}{180} \right) - 8.88543 [\sin(2\phi_2) - \sin(2\phi_1)]$$

where

E_x = East error in nautical miles

E_y = North error in nautical miles

APPENDIX C

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